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The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes

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THE ORIGIN AND MODE OF EMPLACEMENT OF THE GREAT TUFF DEPOSIT IN THE VALLEY OF TEN THOUSAND SMOKES

by

Clarence N. Fenner

During the early history of the post-eruption explorations of the Katmai region in Alaska under the auspices of the National Geographic Society, Robert F. Griggs, the director of the expeditions, recognized that the very thick deposit of ash and pumice that covers the floor of the Valley of Ten Thousand Smokes and extends into adjacent depressions, possesses features which differentiate it from the much thinner mantle of ash spread over the general region.

The thinner mantle of ash was naturally to be attributed to material thrown violently into the air by the explosive eruption of Mount Katmai, but in order to account for the peculiar features of the tuff deposit in the Valley a somewhat different explanation must be sought.

Griggs' narrative of the discovery of the Valley and its exploration, and his description of its more prominent features are to be found in several articles of great interest published in the National Geographic Magazine and the Ohio Journal of Science.[1]

The views that he held at this earlier period regarding the origin of the tuff deposit are set forth at some length in the article, "The Great Hot Mudflow of the Valley of Ten Thousand Smokes." For details of the theory and the reasons leading to his conclusions, reference may be made to the original article. In a few words, it may be said that he believed the material was ejected as a hot mud from fissures in the floor of the Valley and in Katmai Pass, and spread with great rapidity over the region it now occupies (see map, pages 4 and 5).

The difficulties connected with the idea of the extrusion of a mass of mud from the interior of the earth were recognized, and his attitude was expressed in the words: "I would further add that I am not committed to any theory of the origin of this curious terrane, but will be glad to accept any other interpretation that can be suggested, provided only that it is consistent with the facts as found in the field. Certainly any suggestion that would relieve us of the necessity of postulating an entirely new type of volcanic action will be most welcome."

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[1] Griggs, R. F., The Valley of Ten Thousand Smokes: Nat. Geog. Mag., vol. 31, pp. 12–68, 1917.

———, The Valley of Ten Thousand Smokes: Nat. Geog. Mag., vol. 33, pp. 115–169, 1918.

———, Are the Ten Thousand Smokes Real Volcanoes? Ohio Jour. Sci., vol. 19, pp. 97–116, 1918.

———, The Great Hot Mudflow of the Valley of Ten Thousand Smokes: Ohio Jour. Sci., vol. 19, pp. 117–142, 1918.

———, The Character of the Eruption as Indicated by Its Effects on Vegetation: Ohio Jour. Sci., vol. 19, pp. 173–209, 1919.

See also a book by the same author entitled The Valley of Ten Thousand Smokes, published by the National Geographic Society after this article was in type.

J. D. Sayre and P. R. Hagelbarger, A Study of Temperatures in the Valley of Ten Thousand Smokes: Ohio Jour. Sci., vol. 19, pp. 249–278, 1919.

J. W. Shipley, Some Chemical Observations on the Volcanic Emanations and Incrustations in the Valley of Ten Thousand Smokes, Katmai, Alaska: Am. Jour. Sci., vol. 50, pp. 141–153, 1920.

During the field season of 1919, in which several members of the Geophysical Laboratory participated, the question of the origin of the deposit was reviewed and was the subject of earnest investigation and frank discussion. From the relations as seen on the ground, it seemed quite certain to all that the main crater of Katmai could hardly have been the point of distribution of the tuff deposit, and also that Griggs' contention that it must have originated within the Valley itself (with possible accessions from certain areas on the lower slopes of the mountains immediately adjacent) was well founded. The main point of discussion with us, therefore, was as to the character of the material at the time of extrusion, whether it had been a water-bearing mud or a mass of hot, dry sand and pumice. Griggs had early recognized effects of high temperature in places, and evidences of this sort accumulated with further exploration.

The seeming impossibility of reconciling such temperatures with the presence of even the minimum amount of water necessary to cause the saturation and flowage of such material as we had to deal with was impressed upon us more and more forcibly, and all finally reached the conclusion that it was necessary to lay aside the conception implied by the term "mudflow" and to postulate different conditions. As expressing the new point of view, the term "sandflow" was adopted by us.

COMMENT ON ESCHER'S VIEWS OF THE TUFF DEPOSIT

In the course of a previous article[1] dealing mostly with other phases of the eruption, I gave a brief account of the "mudflow" or sandflow and an explanation in accordance with the new viewpoint. Somewhat later Griggs, in a non-technical article,[2] presented a graphic description of the scenes that might be inferred to have accompanied the extrusion of torrents of incandescent sand and pumice such as these are believed to have been.

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[1] Fenner, C. N., The Katmai Region, Alaska, and the Great Eruption of 1912: Jour. Geology vol. 28, pp. 569–606, 1920.

[2] Griggs, R. F., Our Greatest National Monument: Nat. Geog. Mag., vol. 40, pp. 219–292, 1921.

Quite recently my attention has been directed to an article by B. G. Escher, "On the Hot Lahar (mudflow) of the Valley of Ten Thousand Smokes (Alaska)."[1] Escher, who had never visited the locality, had reached the conclusion from a consideration of data given by Griggs, (neglecting the article cited in the Journal of Geology) that the "mudflow" of the Valley of Ten Thousand Smokes is strictly comparable and similar in origin to the "lahars" (flows of hot mud) from the Klut volcano, Java, especially to that of 1919. Escher's views are summarized in his last two paragraphs:

> However this may be, his [Griggs'] detailed observations communicated in lit. 5, have convinced me that the tuff-filling of the "Valley of Ten Thousand Smokes" is brought about by a hot lahar coming from the crater lake of Mount Katmai.
>
> We can therefore predict with a great approach to certainty that at the next eruption of Katmai volcano hot lahars will again occur, and principally on that side or those sides where the crater rim is now lowest.

Certainly, no investigator can justly raise objection to having his work carefully reviewed by others and a different interpretation put upon the data, if such seems warranted. In this case, however, Escher, in arriving at his conclusions, has neglected data supplied by the text of Griggs' articles and by a map accompanying them, which render practically impossible such a mudflow as he assumes; and has, morever, made a curious misinterpretation of certain figures supplied by Griggs, thereby arriving at a wholly unwarranted belief in the former existence of an immense crater lake on the summit of Mount Katmai. In order to correct possible misconceptions to which such an article may give rise, and to justify our own conclusions as to origin, it seems desirable to set forth in more detail than has yet been done certain features of the deposit and its relation to other phenomena of the eruption.

Escher has calculated[2] that the volume of the Klut lahar of 1919 equalled 40 to 100 million cubic meters, and that the capacity of the

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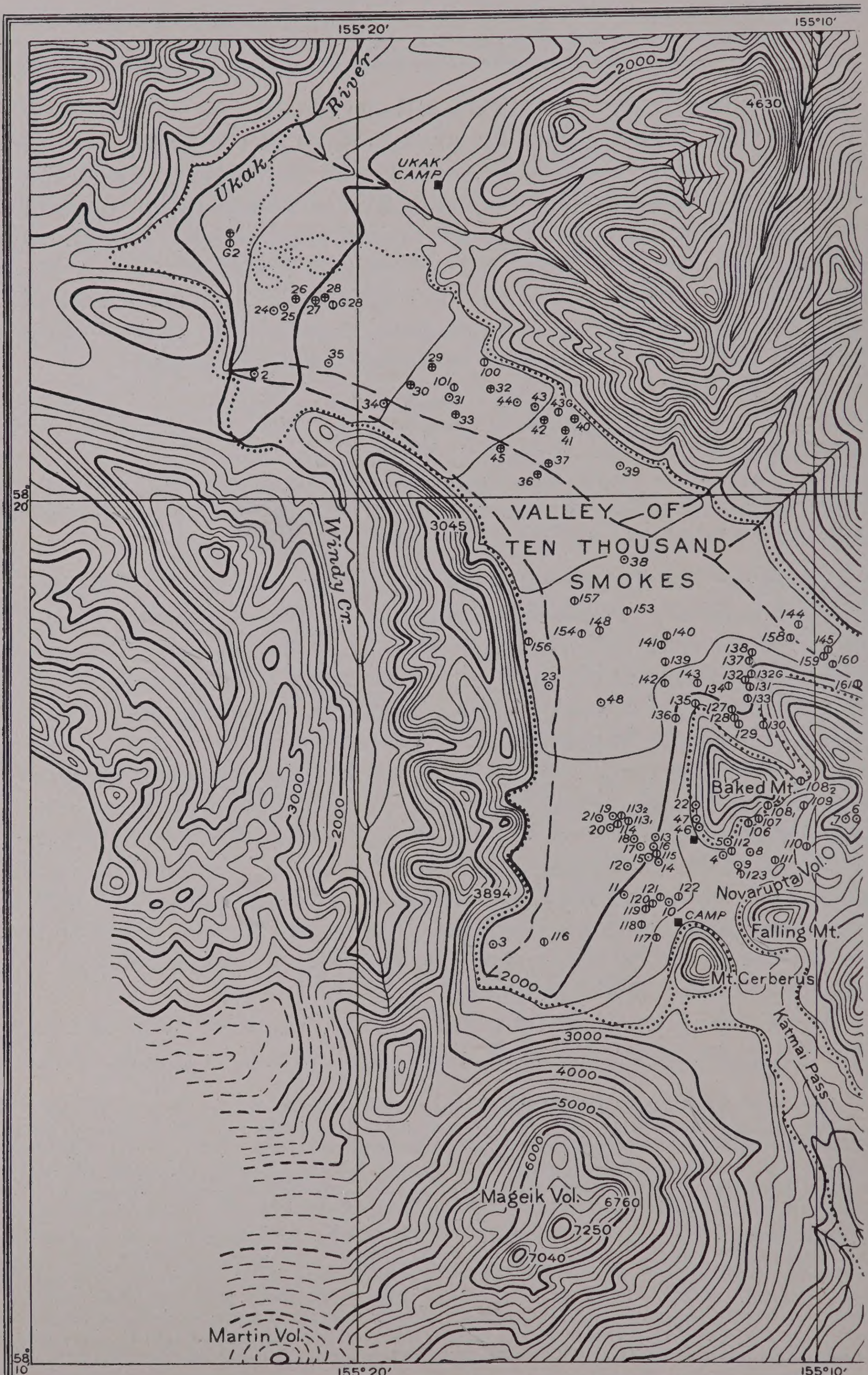
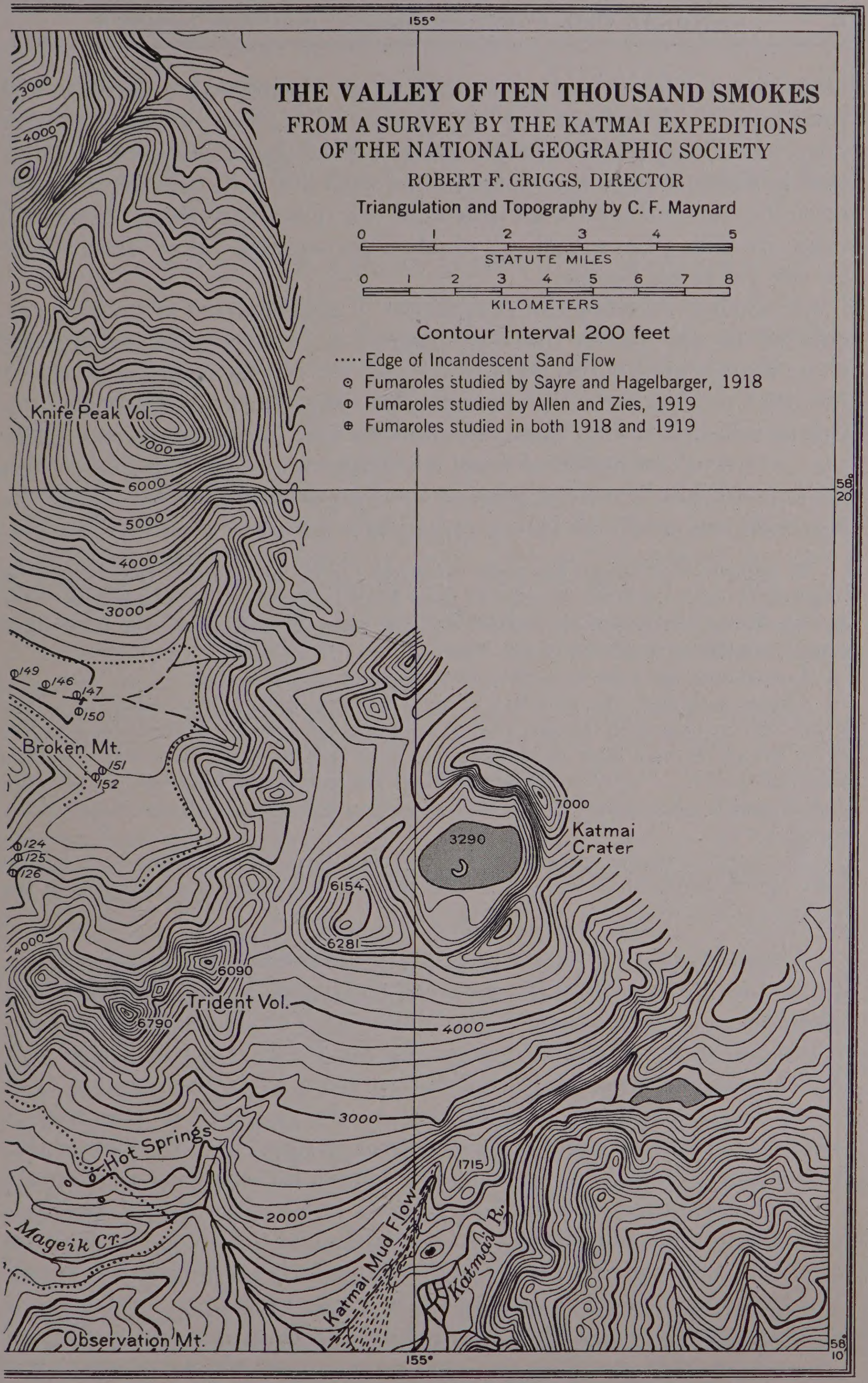
[1] Escher, B. G., Proceedings of the Royal Academy of Amsterdam, vol. 24, pp. 282–293, 1921.

Since the present article was written, Griggs has informed me that he had recently had some correspondence with Escher with regard to the paper mentioned above, and had sent to him an article thereon for publication in the Proceedings of the Royal Academy of Amsterdam. Escher has now frankly admitted that he was misled in his interpretation of the sandflow. However, as Griggs' treatment of the subject is quite brief and as it seems desirable to present for the information of those interested all the data that have been collected relevant to this remarkable deposit and to discuss their interpretation, I have followed a suggestion made to me that it would be well to allow this article to stand as written, as an independent description, prepared without previous knowledge of Griggs' paper. This status of the matter should be understood by the reader and the arguments offered herein should now be regarded not as directed specifically in reply to Escher's paper, but rather as an effort to dissipate any feeling of uncertainty regarding our interpretation that may be held by other volcanologists for lack of full information. For Griggs' article, see Proceedings of the Royal Academy of Amsterdam, vol. 25, pp. 42–50, 1922.

[2] Op. cit., p. 286.



MAP OF THE VALLEY OF TEN THOUSAND


THE VALLEY OF TEN THOUSAND SMOKES
FROM A SURVEY BY THE KATMAI EXPEDITIONS OF THE NATIONAL GEOGRAPHIC SOCIETY
ROBERT F. GRIGGS, DIRECTOR
Triangulation and Topography by C. F. Maynard

Contour Interval 200 feet

····· Edge of Incandescent Sand Flow
◎ Fumaroles studied by Sayre and Hagelbarger, 1918
⦶ Fumaroles studied by Allen and Zies, 1919
⊕ Fumaroles studied in both 1918 and 1919

SMOKES AND THE ADJACENT VOLCANOES

lake in the Klut crater amounted to 38 million cubic meters. The solid material is believed to have been derived from a new explosive eruption taking place through the waters of the crater lake "so that this is blown out of the crater mixed with hot ash, pumice, and volcanic bombs and lapilli, all of which flow down the slopes of the volcanic cone as a hot mudflow, which is known as a 'lahar' (hot lahar) by the Javanese people."

In such a mixture the proportion of solid matter to water is calculated as $\frac{40}{38}=1\pm$ in the one case, or $\frac{100}{38}=2.6$ in the other, and these figures are held to be indicative of the relative amount of water required to impart to the mixture the ability to flow. I have no desire to take issue with these calculations and, indeed, have no doubt that overflows of hot mud from a volcano may be generated in this fashion. Escher, however, goes on to apply similar calculations to the Katmai case, and falls into a remarkable error.

> It appears that Griggs has quite overlooked in his speculations that before the eruption of 1912 the Katmai volcano must have possessed a crater lake, just as is now the case according to his section, and the water of this crater lake must have acted a similar part as that of the Klut. . . .
>
> Let us now trace the quantities of solid material and water.
>
> Griggs estimates the quantity of solid material of the great mudflow of the Valley of Ten Thousand Smokes at 4096 million cubic meters and the cubical capacity of the crater hole after the eruption at 4500 million cubic yards = 3442 million cubic meters. . . . According to Griggs the crater hole had before the eruption of 1912 a cubical capacity of 11,000 million cubic yards = 8415 million cubic meters.
>
> The content of the crater lake will therefore have amounted to 8415 million cubic meters before the eruption; so that the above mentioned proportion for the Katmai volcano would amount to $\frac{4096}{8415}=0.49$.[1]

These figures of Escher's relating to the present and former capacity of the crater, which he ascribes to Griggs, have evidently been taken from Griggs' article "The Valley of Ten Thousand Smokes" in the National Geographic Magazine for February, 1918, page 168, but their significance is quite different from what he supposes. The figure of 4500 million cubic yards for the capacity of the present crater is, indeed, correctly quoted from Griggs, but that of 11,000 million cubic yards for the capacity before the eruption is not only a misinterpretation of what Griggs says, but implies that Escher has failed completely to understand Griggs' description of the form of the mountain before the eruption and of what took place during that event.

The figure of 11,000 million cubic yards arrived at by Griggs is not the capacity of the crater before the eruption, but is Griggs' estimate of the capacity of the present crater plus the volume of material in the peak that rose above the crater and disappeared. In other words, Griggs' calculation of 11,000 million cubic yards represents what he believed to have been blown away from the mountain during the eruption.

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[1] Escher, B. G., op. cit., p. 287.

CONDITION OF KATMAI BEFORE THE ERUPTION

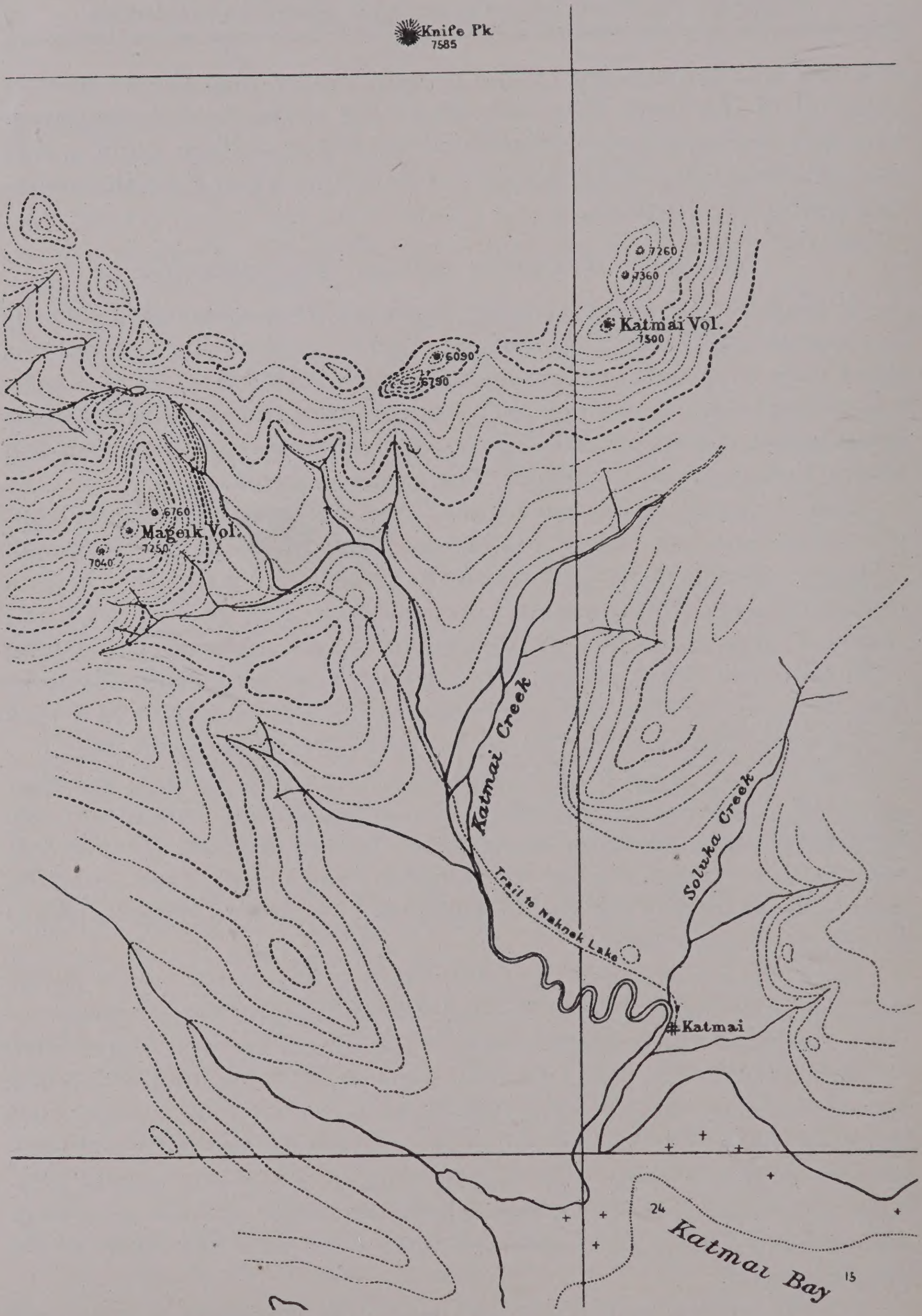
It may be suggested by some, however, that although Escher is in error in supposing that Griggs' figures support his contentions there may have been, nevertheless, a large crater lake on the summit of Katmai. It will be well to consider this possibility. Our information regarding this region, little explored and little mapped before the eruption, is meager, but seems sufficient.

Two maps of the United States Coast and Geodetic Survey supply information of value. No. 8502, Cape St. Elias to Shumagin Islands ("Authorities: Surveys to 1915 and other sources"), is on a moderate scale (approximately 1 : 950,000, or 1 in. = 15 mi.) and covers a wide area; No. 8555, Shelikof Strait and Afognak Island ("Authorities: Original surveys from 1897 to 1908 with additions from Russian surveys and other authorities") is on a scale of 1 inch to 3¼ miles (approximately). A portion is reproduced on page 8.

The two maps are a little inconsistent in minor details, but they agree in representing Katmai as a triple-peaked mountain, the heights of whose summits are given as 7500, 7360, and 7260 feet. A comparison of page 8 with the detailed map constructed from the later surveys of the National Geographic Expeditions (pages 4 and 5) shows good agreement.

With the exception of Katmai, those peaks of the range visible from Shelikof Strait, and even the lesser physiographic expression of the country on the southeast side of the range, are well represented on the Government map. Katmai alone shows a striking difference, but nevertheless its old form can without difficulty be brought into harmony with the form of the stump shown on the National Geographic Society's map. The map plainly indicates the former presence of at least two peaks, into which the crater pit now cuts huge embayments, and a third may well have risen over the center of the present crater.

I think we are well justified in accepting the maps of the Coast and Geodetic Survey as correct in representing Katmai with three peaks before the eruption, each of which rose to something of an apex, and in a mountain of this form there was no room for the great crater lake that Escher's theory demands. Further on Escher says:



MAP SHOWING OLD FORM OF KATMAI VOLCANO

The site of the peak labeled Katmai Volcano on the map and of the two peaks to the northeast of it is now occupied by the great crater pit. A portion of the United States Coast and Geodetic Survey Chart No. 8555, reduced to a scale of approximately 4¼ miles per inch.

What still calls for an explanation is the fact that the mudflow has not been found between the western crater rim (±6000 feet = 1820 m.) and the contour-line of 3000 feet (910 m.). A similar phenomenon, though less striking, is also observed at the Klut. It is due to the fact that the lahar erodes in the shorter and steeper upper part of his course and can lay down deposits only within the much longer and more level lower part. The name Klut signifies: sweeper; at each eruption he entirely clears away great parts of his slopes and further on sweeps away cultivations and villages.[1]

A FLOW OF HOT MUD FROM KATMAI WOULD HAVE MELTED ITS GLACIERS

This description of the erosive work of the lahar is interesting and important in connection with Katmai, from the fact that these western slopes over which a hot mudflow or other torrent of hot material from Katmai would necessarily descend in reaching the head of the Valley of Ten Thousand Smokes are covered with great glaciers, extending from the rim downward almost to the valley floor. All ascents of Katmai up to the present have been made from the southerly side and have reached the notch in the southern rim. From this point (according to notes on my ascent of August 10, 1919):

> A glacier extends nearly one-third the way around the rim on our left (westerly to northerly). The walls of this beheaded glacier stand in vertical cliffs, probably 100–150 feet high, and come within a very short distance of the rim. They give no obvious indication of having been acted upon by blasts of intense heat during the eruption.[2]

From the floor of the Valley of Ten Thousand Smokes (especially from the southeastern arm of the Valley) this glacier or assemblage of glaciers is plainly visible (page 10). They lie along a great depression which extends from the low western side of the rim, down across the middle slopes of the mountain (in a gulch or trough more definite than is indicated on the contour map) and on into the depression on the southerly side of the isolated peak near the valley floor. These glaciers, then, occupy the floor of that depression which a mudflow or sandflow would naturally follow from the crater to the Valley. Now we must remember that the deposition of the tuff in the Valley antedated the main eruption of Katmai,[3] so that the glaciers

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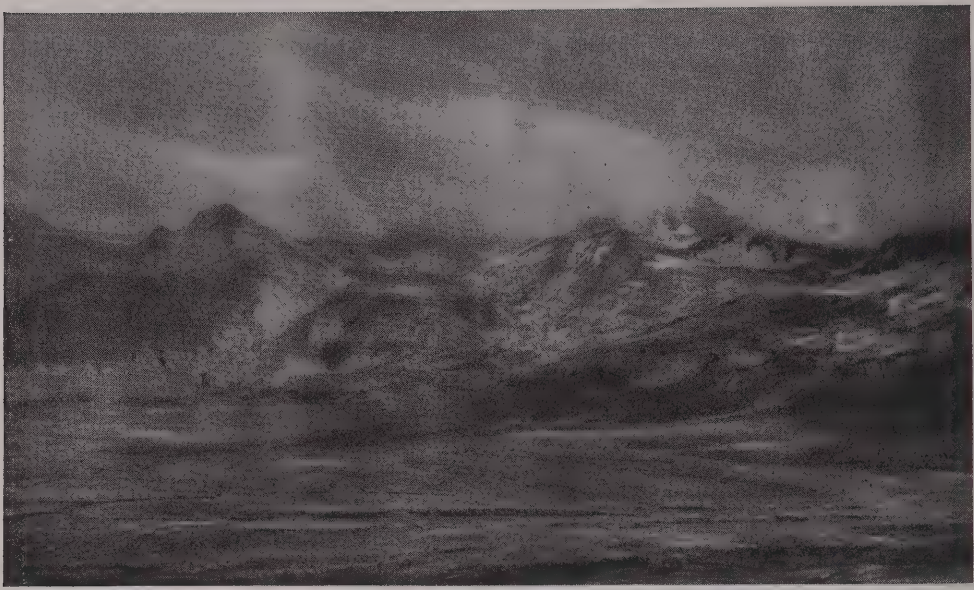
[1] Escher, B. G., op. cit., p. 289.

[2] There may be a query as to why this glacier wall fronting the crater was not melted by the eruption in progress in the immediately adjacent crater, even though no lahar or tuff avalanche poured over its surface. In answer to this the natural supposition is that subsequent to the eruption parts of the crater rim have slumped away at this point (and probably at others), exposing to present view walls of ice that were not exposed to the heat of the eruption, and that the only heating to which these portions of the glaciers were subjected was that relatively insignificant quantity imparted by deposition of sand and pumice upon them, that had been thrown high into the air and fallen back in a somewhat cooled state.

[3] Evidence of this has been given in previous publications, but will be taken up again in this article.



Photograph by P. R. Hagelbarger, 1918

GLACIERS ON WEST SIDE OF MOUNT KATMAI

The great trough in the center of the picture is occupied by a glacier extending from the crater rim of Katmai down to the head of the southeast arm of the Valley. A portion of the southwest wall of the crater shows through the clouds at right of center.

were not protected at this time by even that covering of ash which they later received. It would seem, therefore, that a descent of a huge quantity of hot tuff over them, either as a mudflow or as a sandflow, would melt them completely or produce an entirely abnormal aspect.

EFFECT OF SANDFLOW ON GLACIERS OF COTOPAXI

Regarding the effect of a flow of hot sand over a glacier, there is evidence from another source that seems quite direct—namely, an account given by Theodor Wolf of an eruption of Cotopaxi in 1877.[1] The eruption itself was not seen by this author, but he visited the region about two months later and described the eruption and its effects from the accounts of eyewitnesses. The outbreak was evidently regarded by him as necessarily that of a mass of liquid lava, but the manner of outburst (over all parts of the crater rim, high and low, simultaneously) and other features that he describes were looked upon as very extraordinary. Later on I shall return to his account and point out how well his description accords with what has subsequently come to be recognized as the characteristics of *nuées ardentes*.

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[1] Wolf, Theodor, Der Cotopaxi und Seine Letzte Eruption am 26 Juni, 1877: N. J. Min., 1878, 113–167. Material quoted from pp. 133–135.

After describing the outbreak itself, he goes on:

> Floods of water and mud. The sudden outflow of an enormous amount of fluid glowing lava over the volcanic cone covered with thick layers of ice and snow must have as a consequence the melting down of a great part of these layers. There were generated simultaneously around the whole circumference of Cotopaxi great masses of water that rushed down its steep slopes as torrents or cataracts. . . .
>
> The glowing lava, although in the uppermost parts discharged with force over gullies and crests and often across ridges, must soon collect in great masses in the broad troughs and push downward in them. In consequence enormously broad and deep channels were furrowed out in ice and snow, and great streams of water generated. Observation has shown me in the clearest manner that the water and mud masses (the so-called avenidas) in every single quebrada [gulch] stand in relation to the channels excavated in the ice above them as their direct upward prolongation, and further that the channel, for its part, is related to the lava mass[1] that came down through it. This observation is important for the correct explanation of the floods of water and mud. Only one or two small gulches on the northeast side of Cotopaxi were fortuitously spared from the avenidas; all the rest were more or less heavily filled with them, most heavily those directed toward the west and east. . . .
>
> In the upper and middle parts most of the gulches, although narrow, were deep enough to hold the stream, but where they come out on the more gently inclined plains and possess no high banks, it poured without limit over fields, pastures, haciendas, roads, etc., destroying and carrying everything away with it. From Callo to Latacunga the plain presented the appearance of a great lake of mud in wildest agitation.

At several favorable points of observation on the east slope of Cotopaxi, Wolf estimated the depth of the channels cut in the ice as 40 to 50 meters. He remarked that they were not developed on the very highest parts of the mountain, but only farther down the slopes. This supports other evidence which seems to rule out the idea of the emptying of a crater lake, and also that of a flow of liquid lava.

Evidences of such a catastrophic deluge as Wolf described, if it occurred on the glaciers of Katmai, should have been visible after a number of years. I took special note of the character of the glacier surface during the summer of 1919, in considering the feasibility of an ascent of the mountain from this side, and saw nothing to suggest the passage of a flood or avalanche of hot material over it. It is true that crevasses and séracs were abundant, but they appeared of the normal sort, such as were encountered on the glaciers of Mount Mageik on our way to the ascent of Mount Martin. To an observer on the ground the likelihood of the tuff deposit of the Valley having come from Katmai Crater appears so slight as to be almost negligible. I have recently discussed the subject anew with Allen and Zies and they both agree with this view of the matter.

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[1] The "lava mass," as later described, is composed of fragmental material.

But since few people have seen the terrain and since the matter is one of such importance in its bearing upon the whole mechanism of the eruption, it seems advisable to present all the evidence.

DISTRIBUTION OF TUFF PRECLUDES KATMAI AS SOURCE

According to a diagram that Escher prepared, based upon the map of the Valley accompanying Griggs' article,[1] and reproduced on pages 4 and 5 of this article, he supposed the mudflow from the crater, upon reaching the head of the Valley, to have divided. One part is represented as flowing northwest down one of the two main arms of the Valley, and the other as passing in two streams between Baked Mountain and Trident into the second main arm of the Valley. Here it divided again, one part flowing northerly and the other southerly.

In indicating such courses, Escher seems to have paid little attention to the contour lines given on the map. The part that he supposed to have passed between Falling Mountain and Trident would have had to climb a precipitous mountain wall several hundred feet high (see page 14). His idea as to this detail may be disregarded at once, but in other places also the ascent of slopes is indicated, whose grade is more gradual to be sure, but whose total rise is considerable. The problem which Escher had to solve, and which must be solved by anyone proposing a derivation from Katmai or any single orifice of extrusion, is to explain the distribution of the material in such a manner as seemingly to require upgrade movements.

The matter cannot, however, be lightly dismissed, for we must consider the possibility that the process of accumulation and later distribution was such that piles or heaps of material rose until they surmounted divides and spilled over on the far sides, and that later the original accumulations were partly drained away. Some support for this idea may be supposed to be found in that curious feature which Griggs has called the "high mud mark" or, later, the "high sand mark." [2] This is the top of a slope of moderate pitch (in places the top of a shelf or terrace) by which the general level of the surface of the tuff deposit is connected with the abrupt slope of the surrounding mountains. Its elevation is generally 100 to 200 feet above the level of the tuff.

Griggs' description indicates that it is to be found everywhere, as a bounding feature of the Valley deposit, except in the near vicinity of the new volcano Novarupta. To me its continuity did not appear quite so unbroken. At places it was plainly visible for long stretches;

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[1] Ohio Jour. Sci., vol. 19, p. 138, 1918.

[2] Griggs, R. F., Ohio Jour. Sci., vol. 19, p. 121, 1918; Nat. Geog. Mag., vol. 40, p. 232, 1921.

elsewhere it seemed to fade out and disappear. Nevertheless I believe that this does represent a "high sand mark." The difference between this level and the present general surface, however, I would not ascribe to a draining away of material, as was postulated in our hypothetical case, but to a gradual settling down and packing together of the loose powder of which the deposit largely consisted when movement ceased.

Nowhere have we seen a suggestion that great accumulations were heaped up at any place in the Valley. Except for the relatively unimportant transitional slope connecting the high sand mark with the general surface of the tuff, the latter extends as an almost plane surface [1] to an intersection with the more abrupt slopes of the surrounding mountains. One of the most striking and surprising characteristics of the tuff deposit is the absence of any indication that it ever accumulated in masses heaped above the general level, or that anything in the nature of a marked head (in the hydrostatic sense) existed; and whatever theory of its origin be adopted, this is still a surprising feature. Nevertheless, in any theory of distribution from a single source, the very considerable divides now existent between adjacent portions of the deposit would have had to be surmounted by accumulations back of them.

There are several places where this would be required. Let us suppose that a flow from Katmai crater did reach the head of the southeastern branch of the Valley, in spite of the objections already presented. Its movement from this point northwestward down one of the great branches of the Valley, and then down the main Valley, would be almost unobstructed, but how would it enter the great southern branch of the Valley?

The only route which seems possible for a moment is that which leads from the head of the southeastern branch through the straits bounded by Novarupta and Broken Mountain on the one hand, and Falling Mountain and Trident on the other. Not only is this connecting passage narrow, but there is a decided upgrade, gradual at first and then more steep, to the summit of a ridge lying like a dam from Broken Mountain to a jutting spur of Trident (see page 14). The total amount of rise is shown on the contour map as 400 feet (from 2300 feet to about 2700 feet), and I should say it is at least this.

Some deduction will have to be made, however, for the great masses of material thrown out by later explosive activity of Nova-

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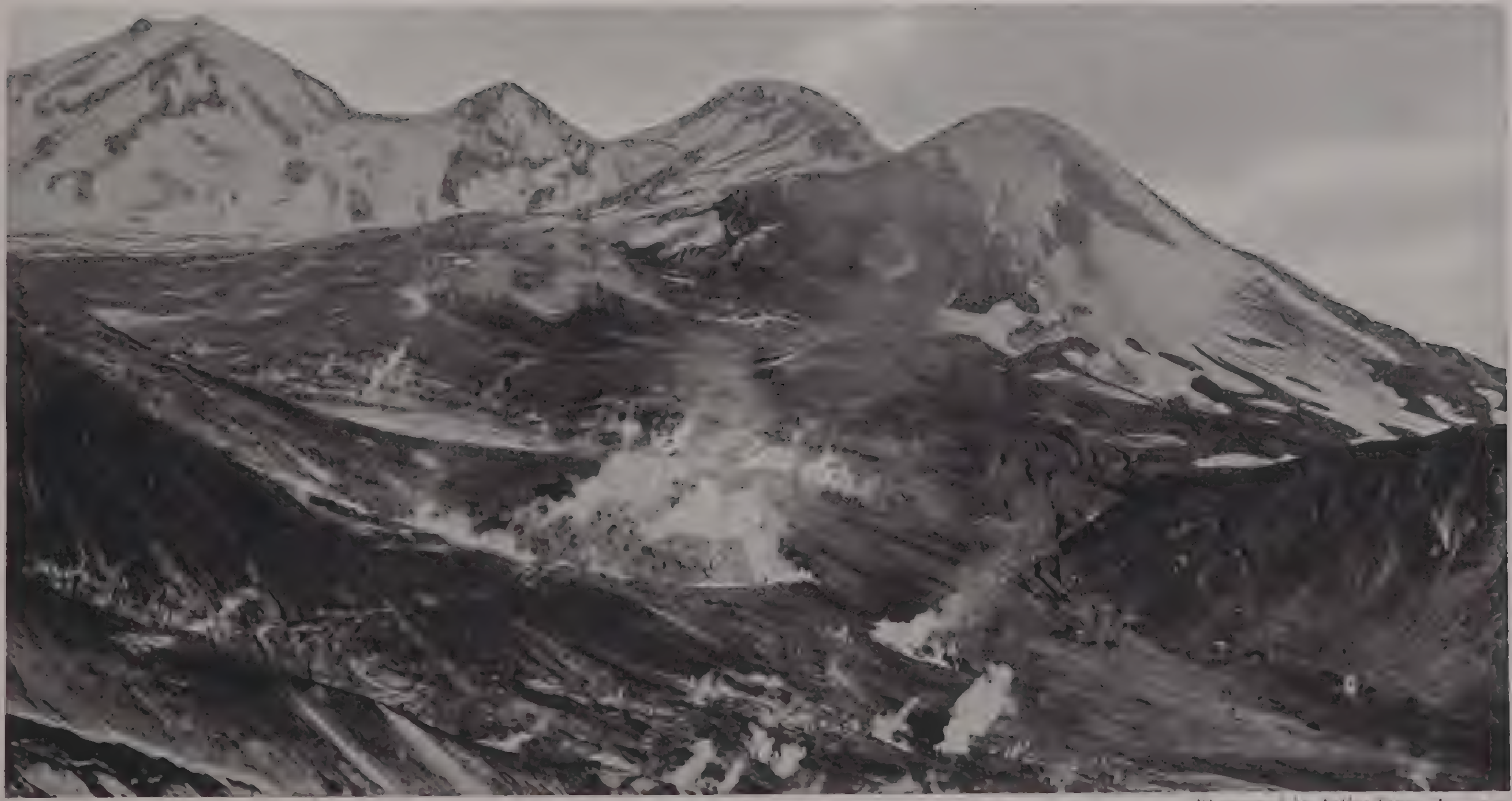
[1] This should not be interpreted to mean a level surface; there is always a moderate slope conforming approximately to the old slope of the Valley, and in many places a very gentle slope from the sides toward the middle.



Photograph by Julius Stone, Jr., 1919

NOVARUPTA AND TRIDENT

In the middle distance appears the ridge that separates Novarupta basin from the southeast arm of the Valley; to the right a part of Falling Mountain. Lines of steam vents are visible on the lower slopes of Trident.

rupta and now covering all else in the vicinity. These deposits are naturally thickest immediately around Novarupta and probably thin rather rapidly in all directions, but I believe that to assign a thickness of 400 feet to them would be quite unwarranted. In recent fault scarps on that part of Broken Mountain immediately north of Novarupta (near fumaroles 6 and 7) sections of Novarupta deposits are exposed to a thickness of about 100 feet. The bottom is not visible, but is probably not very far below. Moreover, no matter how thick these later deposits may be, they could not have built a ridge having the form, position, and strike of this one (except under very peculiar conditions of ejection), unless a ridge existed here after the movement of the sandflow ceased and before the later deposits were laid down.

But if we disregard this ridge, we still find that the hypothesis we are considering meets with difficulties at this point. The surface of the deposit in that area of the Valley which first would have received a flow from Katmai (the head of the southeastern branch) has an elevation of about 2300 feet. If we go westward three miles to the other side of the ridge, we reach an area where the later Novarupta deposits are quite thin, and here again we are at an elevation of 2300 feet. Thus we see that these two points three miles apart are at almost the same level, and the normal flow gradient in the assumed direction is lacking.

But even on the assumption that the great quantity of tuff filling the southern branch of the Valley passed through by this route, the difficulties are not ended. The two branches of the Valley unite just to the northwest of Baked Mountain and Broken Mountain. Here the Valley is widest and the course most unobstructed, but between the two mountains a valley runs back for a mile and a half to the southeast, filled with tuff *whose surface slopes to the northwest.*

It would be possible that during the rush of material past the mouth of this valley a small amount should move backward into this "slack water," but it seems almost impossible to imagine it running backward uphill to a considerably higher level than at the mouth. On the other hand, there are many fissures and much fumarolic activity here, and I should suppose that some of the many sources of supply lay within this valley.

Probably that arm of the tuff deposit which extends over Katmai Pass and down into the valley of Mageik Creek is the one above all others which presents the greatest obstacles to the hypothesis of a derivation from Katmai Crater, and fortunately I have data on elevations here which bear directly on the point at issue.

At the site of Baked Mountain Camp the high sand mark is very prominent, and the camp was situated on this terrace or platform, about 200 feet above the general surface. Its position was on the southwestern side of Baked Mountain, between fumaroles 22 and 47. About 1½ miles away to the south, across the open Valley, is the point between Cerberus and Falling Mountain that may be considered the beginning of Katmai Pass. From this point one rises by a long, gradual slope to the summit of the pass, and thence descends to Mageik Creek.

The pass for its whole length is probably underlain by the sandflow ("mudflow"), though it may be thin near the summit of the pass, and is concealed in many places by later deposits. In the valley of Mageik Creek, and especially where the stream has cut a course through it, it is again very thick. The data on elevations are as follows: On July 29 a party of us left Ukak Camp in the morning and arrived at Baked Mountain Camp at 2.40 p.m. The reading of the aneroid[1] here was 2500 feet. A little before 5.30 p.m. we left Baked Mountain Camp for Camp 4. After descending from the terrace to the valley floor we crossed the valley and ascended to the summit of Katmai Pass, which point was reached at 6.30 p.m. The reading at this point was 2870 feet. Thence we continued to Camp 4,[2] which we reached at 9.30 p.m. The reading here showed an elevation of 390 feet, which will serve as a datum for the next set of observations. On August 12 the aneroid at Camp 4 registered 400 feet at 9.30 a.m. We left at 10.30 a.m. At 2.55 p.m. the summit of the pass was attained and the aneroid read 2940 feet. On arrival at Baked Mountain Camp at about 4.00 p.m. the reading was 2550 feet.

These observations give two satisfactorily concordant sets of readings, made in opposite directions of traverse, under similar barometric conditions. According to one, the summit of the pass is 370 feet above the high sand mark at Baked Mountain; according to the other, 390 feet. Is there any reasonable doubt that the tuff deposit in the pass and in the valley of Mageik Creek did not come up the pass from the Valley of Ten Thousand Smokes, but flowed down the pass in each direction from outbreaks near the summit?

We have now reviewed in considerable detail the evidence regarding a possible derivation of the material of the great tuff deposit from Katmai Crater, not restricting the inquiry to the question of an outflow of mud, but considering whether any kind of outflow from this point would satisfy the conditions. Facts have been cited which seem to exclude such an origin. We have seen, indeed, that not only is Katmai Crater practically an impossibility as a source, but that from no single source, either within or without the Valley, could the material well have reached all the areas where it is to be found.

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[1] The aneroid used was a Taylor Instrument Company's 3-inch engineers' barometer, which had been calibrated at the Bureau of Standards just before departure from Washington in May, and found very nearly correct throughout its range.

[2] Camp 4 was situated on the westerly side of the valley of Katmai River, a little south of the point where Mageik Creek leaves the map (page 5).

TEMPERATURE OF TUFF AT TIME OF EXTRUSION

The evidence on this matter having been presented, the question of the temperature of the material at the time of extrusion will be taken up. The most marked effects are those upon vegetation.

In the region of the upper Valley the adjacent hillsides are now destitute of trees, but this is probably to be ascribed to general unfavorable climatic conditions rather than to effects of the eruption. Areas of similar topographic situation but too far removed from eruptive centers to have been exposed to great heat are likewise bare. Small bushes and herbage doubtless existed but were buried by the ashfall. If the floor of the upper Valley supported larger vegetation, its remains must now be far below the surface. Over a wide area, therefore, no trace of former life is visible from which inferences might be drawn. [1]

In the area of the lower Valley there was evidently a rather thick forest growth, not only on the valley floor but also on the near-by hills. There were extensive stands of poplar, spruce, and birch, and thickets of alders; and a fibrous mat of moss, twigs, and roots seems to have covered the lower ground. The effects of the various phases of the eruption upon these growths were radically different according to whether they were or were not covered by the great tuff deposit. Below its level the vegetation was not only killed but carbonized; above it all the trees were killed but their timber is still sound, and a considerable amount of the lower herbage retained sufficient life to continue growth and push through the covering of ash.

In most places the high sand mark separates in a perfectly definite manner these two classes of phenomena, but locally there are indications of fires having extended above this mark. The death of vegetation on the higher ground can reasonably be ascribed to the Katmai ashfall, though in some places it seems as if this alone were hardly sufficient, and that the presence of noxious gases is indicated. On the

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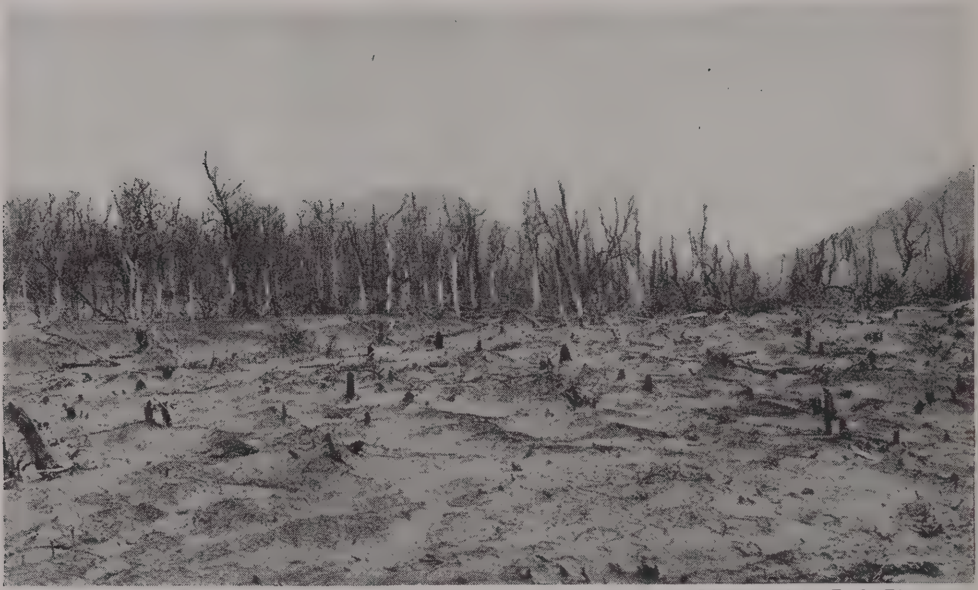
[1] Professor Griggs has informed me that in the extreme western corner of the Valley, on the flank of Buttress Mountain, but close to the toe of the large glacier coming down from Mt. Mageik, remains of good-sized alders have been found. There is also a tradition (how well founded is not certain) that in the old days the last camp below the Pass on the Katmai trail, near what is now the middle of the sandflow, was situated in a clump of trees or large bushes.



Photograph by E. G. Zies, 1919

STUMPS CARBONIZED BY THE SANDFLOW

The foreground is an area occupied by the tuff deposit and later laid bare; standing trees in the background were beyond its margin.

other hand, the carbonization caused by the tuff is in most places so thorough that a high temperature seems to be demanded.

Most of the observations on these carbonization effects were made on that part of the deposit which lies within a radius of four or five miles of Ukak Camp. The site of the latter is a little to the north of the point on the map (see pages 4 and 5) where the intersection of the northern edge of the sandflow with the 1200-foot contour is indicated. In this vicinity the former topography was evidently somewhat rolling and the slopes were gentle. Several low knolls were partly buried by the sandflow and only their tops were left jutting above its surface. Subsequent erosion has uncovered extensive areas of these slopes.

The picture above is typical and illustrates more plainly than a lengthy description the sharply contrasted effects between areas covered by the tuff deposit and those not reached by it. On the latter the dead trees are standing with timber intact; on the former carbonized stumps protrude from a charred mat of peat.

Similar effects are seen on page 22. The intensity of carbonization varies somewhat. Generally the largest trees (which ordinarily run 8–10 inches in diameter) have been completely converted to charcoal down to within a short distance of the old surface of the ground, but occasionally several trunks among a large number are only imperfectly carbonized. Probably the amount of sap or some similar condition exerted an influence. We must remember that the effects described refer to areas near the edge of the deposit, where the depth was not very great and the heat probably not so intense as out in the middle of the Valley, where the old surface is nowhere exposed.

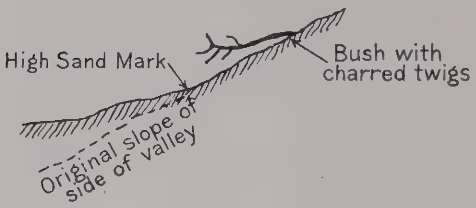
Where portions of trees rose above the surface of the flow we generally find that only the engulfed portion has been changed to charcoal, but there are exceptions to this. In a fairly large number of instances trees standing near the edge of the flow but out of direct contact with it were found to have their upper branches, sometimes of large size, burned off. In such cases it seems either that brush fires were started or that exposure to the heat of the near-by mass caused smoldering combustion to creep up the trunks (see pages 24 and 30).

In one case the trees observed were lying prostrate, their trunks having been carbonized at the level of the top of the flow and their bark charred and pitted by fire all the way from bottom to top. In one of these trees, which measured 8 inches in diameter at the bottom and 5 inches at the top, we found a hole containing carbon 6 feet above the carbonized base, also a burned patch which continued up the trunk for more than a foot. A short distance farther up, 8½ feet from the carbonized base, the trunk had been burned squarely off and stems coming out at this level also showed charring. Several other trees nearby showed almost identical phenomena. Others showed that the burning through at bottom was not abrupt but extended diagonally up the trunk.

On the southwest side of the Valley similar effects were observed near Three Forks, the point where Knife Creek and River Lethe, flowing down the Valley, unite with Windy Creek, coming in from behind Buttress Mountain. Here are a number of low hills rising a little above the surface of the tuff. They are covered with dead trees, but no carbonizing is apparent. Where the slopes continue beneath the level of the tuff the trees projecting out of this cover are carbonized through just below the surface and some show charring along the upper stems.

Near this place the upper portion of a partly carbonized tree was found, lying prostrate on the surface of the tuff deposit and partly buried in the ashfall from Katmai. Carbonization of the trunk was almost complete on the under side, but on the upper side the wood was only browned. Unburnt limbs, still attached, projected upward through the strata of the ashfall. This tree was exposed in the bank of a cut which showed that the tuff deposit was 12–15 feet thick and rested on a carbonized mat of vegetation, from which a large carbonized tree stump rose. Below the charred mat there was 6 feet of boulder till overlying Naknek sandstone.

Along the west edge of the Valley, at an elevation of about 1400 feet, the striking case sketched below was found. The high sand mark here is 30 or 40 feet above the general level. On the hillside, 6–8 feet above any indication of the high sand mark, small bushes, probably alders, were inclined downhill in the way such bushes often grow in a snowy country. The stems, projecting out toward the high sand mark, were plainly carbonized, but their bases, while discolored, did not seem to be charred and did not break as if they were. This gave rather definite evidence, if such were needed, that the high sand mark was an integral part of the sandflow and possessed a high temperature.



Sketch of bush, inclined toward the high sand mark, whose upper twigs have been carbonized.

The knolls mentioned as occurring near Three Forks seem to be part of a group disposed in an irregular line across the Valley from the mouth of a large tributary valley shown on the map a little to the east of Ukak Camp. These knolls show no outcrops of rock and are believed to be morainal dumps. They may be considered to mark the northwestern limit of the Valley of Ten Thousand Smokes proper, but depressions between them connected this valley with that of Ukak River.

The sandflow, coming down the Valley of Ten Thousand Smokes, seems to have been obstructed by this line of knolls; and most of it was diverted through a rather narrow neck in the vicinity of Three Forks before entering Ukak Valley, but some of it found its way along the depressions between the knolls and formed long tongues that entered Ukak Valley by this more direct route.

The map has been generalized here; it should show several more of these knolls than are indicated, and also tongues of the sandflow stretching across the area that is represented as free from them. These tongues of the flow seem to have retained sufficient heat along their whole course to carbonize trees that were buried and to char branches and twigs several feet above the level reached by the tuff.

Sufficient of the sandflow entered the valley of Ukak River so that bluffs 30 feet high above the present river bed are found (see page 22) and the deposit may be considerably thicker. Down this valley toward the northeast, however, it thins rather rapidly and in a few miles seems to have come to an end, but even at the point where its northeastern tip is shown on the map, burnt stumps of small trees were seen.

In Escher's account of the Klut lahar attention is called to the amount of heat that remains after the water has partly drained away and in part evaporated.[1] He says: "Vissering mentions that a walking-stick which four days after the eruption of 1901 was poked into the lahar, was drawn out in flames."

Without further information, such retention of heat by a water-borne mud seems unintelligible. Possibly great blocks might have been transported, whose interior mass remained at a high temperature, or possibly fumaroles breaking through from the depths accounted for the heat, but a discussion without more information is hardly warranted.

In the case of the deposit in the Valley of Ten Thousand Smokes, however, I feel that it would be entirely impossible for the material of which it is composed to have continued at a high temperature for even a few minutes if it had been mixed with sufficient water to transport it. In the lower part of the Valley, where the charring effects were observed, probably 85 per cent or more of the material is of the size of sand or dust. The remainder ranges through a gravelly pumice to pieces of a few inches in diameter, or occasional larger blocks a foot or two in diameter. Farther up the Valley the material becomes coarser, but even here fine material is preponderant and blocks of large size are lacking.[2] It was not conceivable to us that material of this sort could have been mixed with enough water to permit flowage and at the same time retain the temperature necessary to produce the charring and combustion whose effects we saw. For this reason we agreed that the idea of a mudflow must be abandoned.

EXPLOSIONS PROBABLY CAUSED BY HOT SAND

Although the charring of vegetation affords the best evidence that the tuff was very hot at the time of emplacement, there are other effects that seem best explained as arising from the same cause, namely, explosions apparently due to contact of the hot sand with water. An example of this in mild form is seen where Windy Creek strikes the edge of the tuff. Its present course swings abruptly to the left and follows for some distance the contact between the edge of the

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[1] Op. cit., p. 284.

[2] Near Novarupta occasional masses having a diameter of several feet are to be found, but these seem to have been ejected during the later activity of Novarupta and do not belong to the sandflow proper.

Photograph by P. R. Hagelbarger, 1918

THE EDGE OF THE SANDFLOW NEAR ITS TERMINUS

tuff and the old surface. The stream has cut a deep channel here, that is evidently new. A short distance out on the tuff, in the direction the old stream would naturally have taken, are two large, funnel-like craters. These show no indication of present or past fumarolic action and may well be explosive craters.

At a number of other places where streams enter the Valley, very extensive depressions are found which may be due to explosions of this sort. They have probably been modified considerably by later action of streams, and with some of them there is a question, indeed, whether they were not primarily caused by floods. Floods of great volume would be demanded for such action as is shown, and it is doubtful whether the region has experienced such in the last few years from normal causes.

The possibility must be considered, however, that the eruptions themselves produced locally great downpours, whose effect is shown in the depressions we are considering. I do not know of any feature that gives definite evidence of such flood erosion, and certain effects point distinctly to explosive action, but in viewing such features in their modified condition after a number of years, it has not been possible in every case to come to a satisfactory decision among the various possibilities.

One of these depressions is that at the foot of the glaciers of Mount Mageik, which is occupied by the small body of water that Griggs has named Fissure Lake (page 48). Here a great mass of the material of the tuff deposit has been removed by some means, and secondary explosions of the kind suggested seem a reasonable cause. A settling down by fissuring must also be considered among the possibilities here, but the unbroken appearance of the mountain slopes in the prolongation of the lake hardly bears out the idea of a fissure of the magnitude demanded.

In the southeastern branch of the Valley, near the foot of Knife Peak and to the northeast of fumarole 144, a depression was found which shows more distinct evidences of explosive action. The southern end is elliptical in outline, but the northern is broken by the entrance of several gulches. It is probably one-half mile long by 600 feet wide. The bottom is nearly flat; the walls stand about 30 feet high, and the pumiceous strata in them dip perceptibly away from the center on all sides.

On the floor near the edges and on the surrounding slopes are quite numerous angular blocks of indurated material, several feet in dimensions, which must have been broken up and thrown about by some forcible action. The nature of these blocks is of some importance. The color appeared dark-brown in the field, but a dry specimen shows a general tone of medium pinkish-gray. The matrix is of a fine-sandy granularity, and there are numerous inclusions of brown decomposed rock, up to a centimeter in diameter.

The whole has the appearance of an indurated tuff, and the thin section bears this out. The matrix is seen to be composed of small angular fragments of nearly colorless glass, together with phenocrysts of feldspar and pyroxene, and the inclusions are of basic lavas. The appearance of the material is much like that of the recent tuff, but it is much more indurated and its inclusions much more decomposed. I am inclined to regard it as a hardened tuff of considerable age that formed a layer at or near the old surface along a stream or wet piece of ground at the time when the sandflow spread over it, and to suppose that the ensuing explosions broke it up and threw it broadcast.

The fragmental glass of which it is composed is probably to be correlated with the strata of pumice and glass which were found intercalated with peat in an old bog near Ukak Camp, where a recently diverted stream has exposed a deep section. This shows that at intervals in the last few thousand years thin deposits of siliceous pumice were spread over the region.

Photographs by C. N. Fenner, 1919

TREE NEAR THE MARGIN OF THE SANDFLOW, WITH LOWER LIMBS AND UPPER TRUNK BURNT

TREE NEAR THE MARGIN OF THE SANDFLOW, WITH THE UPPER PART OF TRUNK BURNT OFF

Other possible examples of secondary explosive activity are to be seen in the rather abnormal-looking depression which is followed by the stream coming out of the tributary valley on the westerly side of Knife Peak; also in the broad and fairly deep depression which forms the bed of the stream entering the Valley from the easterly side of Knife Peak, for which there seems no other ready explanation.[1]

Near Ukak Camp the temporary ponding of another stream may have arisen from this cause. A depression seems to have been formed just at the margin of the sandflow, as if the flow had advanced to a certain line and stopped abruptly like a wall. Since this would have been abnormal behavior it is suggested that the material actually advanced farther and was thrown out by explosions.

As nearly as one may judge of these secondary explosions from the effects seen after the lapse of a number of years, the phenomena were closely related both in cause and result to those that Lacroix[2] has described as having taken place in connection with the eruptions of Mount Pelée in 1902. There the waters of the River Blanche and the River Sèche were confronted anew after each eruption with a mass of hot material deposited in their beds by the nuées ardentes, and the conflict resulted in explosions which, at times, were of extreme violence.

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[1] These features are to be seen shortly after the streams issue from their tributary gulches upon the tuff-covered floor of the Valley.

[2] Lacroix, A., La Montagne Pelée et Ses Éruptions, pp. 421 et seq., Paris, 1904.

Similar phenomena in St. Vincent have been described by Anderson and Flett.[1] Curtis [2] also has given an interesting account of them in both St. Vincent and Martinique. Such explosions would naturally be expected wherever similar conditions occur.

A RUSH OF WIND ACCOMPANYING THE SANDFLOW

In several places along the borders of the deposit trees had been overthrown or broken off in such a manner as to indicate a high wind accompanying the movement (pages 22 and 30). They lay ordinarily with their tops pointing down the Valley. In places these effects were confined to a rather narrow strip along the edge; in others they penetrated rather deeply into the woods. It was observed that the breaks were of a twisted and splintered sort, such as is characteristic of living wood, so that they can hardly be ascribed to a subsequent gale, especially in view of the close association of the effects with the deposit.

A rather remarkable result was noted on the lower slopes of the Katolinat Range which face directly up the Valley (northwest corner of the map). Over an area of many acres the trees had been broken and overthrown, and the majority lay with their tops pointed *downhill.* The evidence here suggests that the blast of air, coming down the Valley of Ten Thousand Smokes, sweeping across Ukak Valley, and striking the upper part of this high mountain wall, had been overturned in an eddy, so that its force was finally directed down the slope.[3]

RELATIVE SEQUENCE OF THE TUFF DEPOSIT AND THE MAIN ERUPTION FROM KATMAI CRATER

The great mass of the tuff is almost wholly unstratified. Overlying it in most places we find well defined strata of light-gray ash and pumice, which are believed to represent the successive outbursts of Katmai. An effort was made to prove this definitely by comparing

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[1] Anderson and Flett, Report on the Eruptions of the Soufrière in St. Vincent, in 1902: Phil. Trans. of Roy. Soc. London, vol. 200, pp. 353–553. Material cited from pp. 433 et seq.

[2] Curtis, G. C., Secondary Phenomena of the West Indian Volcanic Eruptions of 1902: Jour. Geology, vol. 11, pp. 199–215, 1903.

[3] A hot blast accompanying the avalanches was a prominent feature of the nuées ardentes of St. Vincent and Martinique. See Anderson and Flett, op. cit., p. 450; and Lacroix, op. cit., p. 253.

TABLE I

SECTIONS OF ASHFALL

SECTION 1 ½–1 mile southwest of Ukak Camp; outside of area of tuff deposit but adjacent to it.	SECTION 2 Adjacent to Section 1 (outside of area of tuff deposit).	SECTION 3 At Ukak Camp, outside of area of the tuff deposit of the Valley.	SECTION 4 Covering surface of tuff deposit in Valley, ½ mile±below Three Forks, and 3 miles±south of west from Ukak Camp.
Surface	Surface	Surface	Surface 4 in. probably later surface deposit.
A 2 in. fine-grained material	A 4 in. generally fine material, but faintly banded with coarser.	A 1½–2 in. very fine gray ash; mixture of pumice (glass) and separate crystals.	A? ¼ in. dark-gray grit.
B ¼ in. light-gray grit.	B ¼ in. grit; without discoloration.	B ¼–½ in. yellow; a little coarser than A.	B ¼ in. fine; dark yellow.
C 5 in. grit; pumice and separate phenocrysts; faintly banded within itself; color light-gray tinged with yellow.	C 5–6 in. grit; somewhat stained with yellow; faintly banded.	C 5½ in. sand; consists of pumice and of separate crystals in approximately equal amounts; slight banding, due to differences of color.	C ⅛ in. light-gray sand. 1½ in. dark-gray grit. 1½ in. sand; light-gray with brown shade. 2½ in. sand; light-gray. ¼ in. sand; yellow.
D ½ in. very fine; color white; mostly pumice but with some phenocrysts.	D ½ in. fine.	D ½–¾ in. fine-textured gray ash.	D ¾ in. fine; brownish-gray.
E 4 in. grit; light-gray stained with yellow; pumice and phenocrysts.	E 5 in. grit.	E 5 in. grit; grain increases regularly from top to bottom; pumice and phenocrysts.	E 5 in. dark-gray grit.
F 1½ in. very fine; nearly white.	F 2 in. very fine.	F 4 in. fine-textured gray ash, like A.	F 4 in. fine; light-gray.
G–K 1½ in. gritty layer; light-gray; mostly small pieces of pumice.	G ¼ in. grit.	G ½ in. light-gray grit.	G–K ⅛ in. dark-gray grit. ½ in. light-gray; fine. ¾ in. dark-gray grit.
	H ¼ in. fine; buff.	H ¼ in. fine; light-gray.	
	I ¼ in. grit; dark-gray.	I ½ in. grit; light-gray.	
	J ¼ in. fine; buff.	J ½ in. fine; light-gray.	
	K 1 in. grit; light-gray.	K 1 in. sandy above to gritty below; light-gray.	
Old surface of ground, with moss and twigs projecting up into lower layer and disturbing it.	Old surface of ground.	Old surface, with dark-colored vegetable matter, largely moss.	Unstratified tuff.

IN VARIOUS LOCALITIES.

SECTION 5	SECTION 6	SECTION 7
Covering surface of tuff ¼ mile± down stream from Section 4.	In middle of Valley, between Three Forks and Ukak Camp.	On surface of tuff deposit, ¼–½ mile from northeast margin and about 1½ miles east of south from Ukak Camp.
Surface 15 in. surface wash.	Surface 1 in. later surface deposit.	Surface 2.2 in. probably later surface deposit.
A? ¼ in. gray grit.		
B ⅛ in. brown; fine. ¼ in. light-gray; fine. ⅛ in. brown; fine.	B? ¼ in. brown; fine.	A B Probably missing.
C 1 in. light-gray; sandy. 2 in. light-gray; fine-sandy. 3 in. light-gray, with yellowish tint; sandy.	C 2 in. medium-gray; sandy. 1 in. several indistinct bands of fine and sandy; light-gray. 2 in. medium-gray; sandy.	C 5.6 in. grit with small lumps of pumice.
D ¾ in. fine; light-gray, with brown shade.	D ½ in. light-gray; fine.	D 1.4 in. ill-defined sandy bands.
E 4½ in. dark-gray grit.	E 5 in. medium-gray grit.	E 6 in. grit with lumps of pumice.
F 3½ in. light-gray; very fine.	F 4 in. light-gray; very fine.	F 3.6 in. fine sand.
G–K ⅛ in. dark-gray grit. ½ in. fine; light-gray. ½ in. dark-gray grit.	G ⅛ in. dark-gray grit.	G 0.6 in. grit, with lumps of pumice.
	H ⅛ in. light-gray; fine.	H 0.3 in. sharply marked layers of fine sand.
	I ⅛ in. dark-gray; gritty.	I 0.6 in. grit; lumps of pumice.
	J ½ in. light-gray; fine.	J 0.4 in. sharply marked layer of fine sand.
	K ¾ in. dark-gray; gritty.	K 2 in. gritty layer; lumps of pumice half the diameter of a pea in lower half.
Unstratified tuff.	Unstratified tuff.	Unstratified tuff.

the succession of these strata in measured sections with those that cover the adjacent hillsides, regarding which there can be no doubt.

This might appear to be a simple matter, but uncertain factors enter. We know that during the eruption of Katmai the prevailing winds must have been blowing away from this side of the mountain, for at equal distances on the southeast side the deposits are very much heavier and coarser, and at Kodiak, 100 miles to the southeast, one-half as much ash fell as at Ukak Camp, 14 to 15 miles to the northwest. What fell on the northwest side must therefore have been ejected violently in this direction or have fallen during temporary lulls.

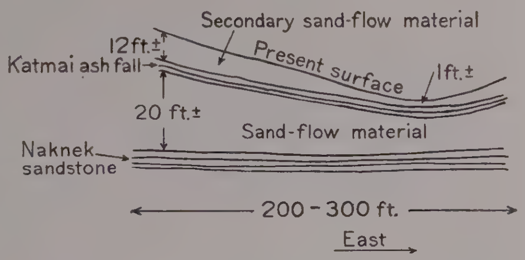
It should not be surprising, then, that the distribution in adjacent sections should have been uneven. Moreover, in the several years that have elapsed since the eruption, the surface of the Valley has been swept at times by strong winds which have formed secondary deposits. It was necessary to use considerable caution to see that the measured sections were ones of original deposition, and even then the uppermost portion was likely to have been carried away or to have had additions made to it.

As a basis for correlation, several sections of the material covering the general country in this vicinity will be given. It should be noted that the measurement of any individual layer of a section is subject to some uncertainty, because the boundaries are often not sharp. Attached letters show supposed correlations (see pages 26 and 27).

The correspondence among these sections is not exact, but perhaps as good as could be expected when the conditions of deposition are considered. They begin at the bottom with several thin layers (G–K) of alternately coarse and fine material, with only a general correspondence among the sections; then comes a layer (F), usually 3–4 inches thick, of light-gray to white, fine to very fine sand or dust. This is followed by 4–6 inches of gray grit (E), then by ½–¾ inches of fines (D), and 5–6 inches of sand in which banding is observable (C). There is then a narrow but sharply marked band (B), and, finally, indications of a fairly thick surface layer, often partly or wholly gone.

The correspondence between the stratified deposits on top of the tuff and those covering the general landscape (which latter certainly came from the eruptions of Katmai) seems sufficiently close to justify the conclusion that the former also represent the Katmai ashfall, and that where these relations were found the tuff deposit antedates the eruption. In those places near the edge of the tuff where erosion has laid bare the old surface of the ground there is no indication of stratified deposits at the base.

In the upper part of the Valley the overlying deposits become coarser and heavier. In the southeastern arm this is to be ascribed to close approach to Katmai; in the southern arm the relations are complicated by ejecta from Novarupta. It had been intended to carry the measurement of sections into the southeastern arm at least, and to determine whether the strata here could be correlated with the great beds of Katmai ejecta found on the other side of the mountain range, but among numerous matters that seemed more insistent no opportunity was found.

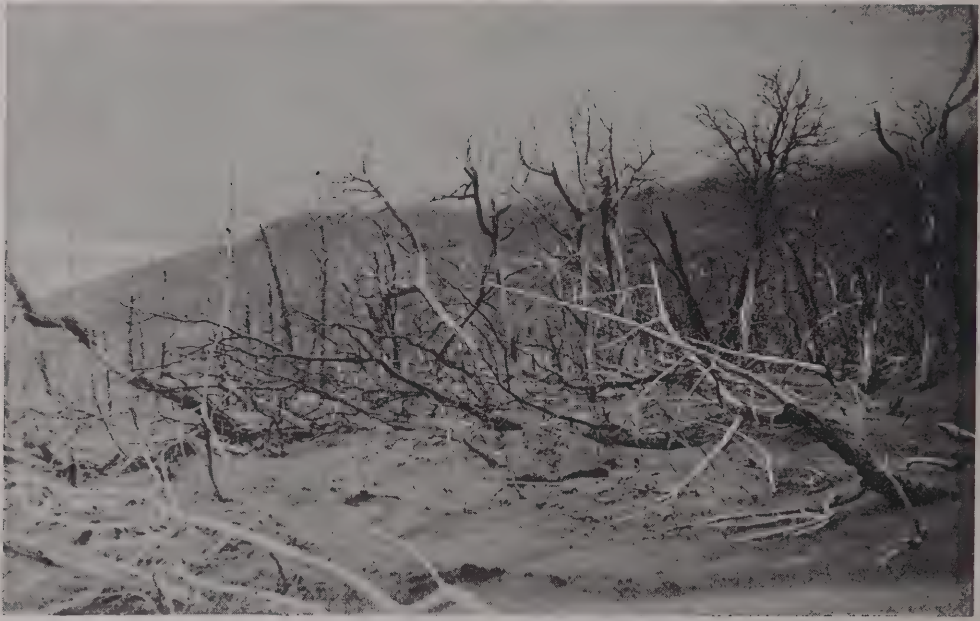


Section of the sandflow near Three Forks, where the strata of the ashfall from Katmai are found between two portions of the sandflow.

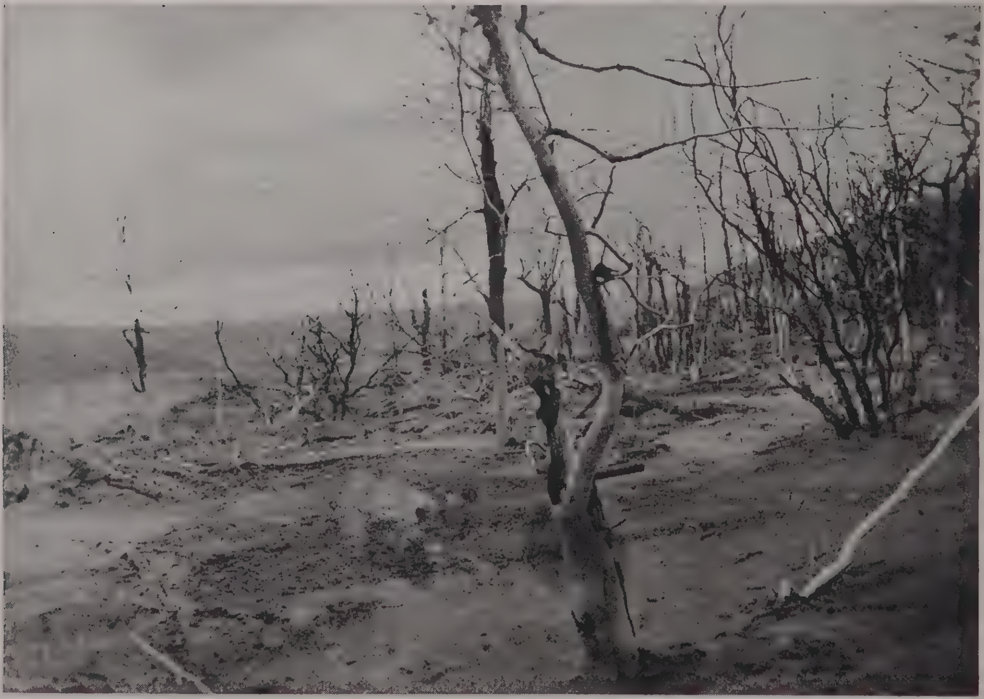
In several places near Three Forks it was found that the stratified ash did not cover the surface but appeared as an intercalated deposit between two layers of tuff. The relations at one place are shown in the accompanying sketch. This seems to mean that after the first sandflow occurred a considerable depression was scooped out in its surface, then came the Katmai ashfall, then a second movement of sandflow material. The uppermost tuff deposit here shows a faint stratification, but in other respects is like the mass below.

Along the narrow gashes in the tuff cut by Knife Creek and River Lethe certain phenomena were observed in several places which have always remained puzzling and for which I have no very satisfactory explanation. Occasional strips of stratified material, perhaps 15 to 20 feet long as a maximum, appeared to be intercalated in the tuff deposit. These often had abrupt terminations and some of them were considerably flexed. They were seen in the nearly vertical canyon walls in almost inaccessible situations, and no opportunity to examine them closely was found. They were all probably in the upper part of the section, that is, within 20 feet of the top.

They may be remnants of Katmai ash, covered by a later deposit of tuff, but another possibility has suggested itself. When we first came into the Valley (in June) we found that there was no water flowing in these canyons, and great heaps of wind-blown sand had piled up in them. Later, when the drainage supply of the basin was increased by the melting of snow and ice on the slopes of the volcanic range, considerable streams again flowed along these channels, and the sand drifts were carried away. It seems possible that occasionally a strip of this secondary deposit might be left in a recess or on a



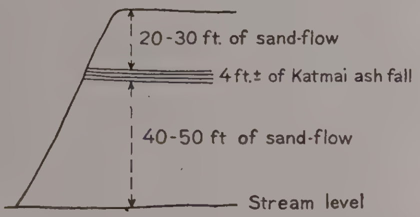
OVERTHROWN TREES AT THE MARGIN OF THE SANDFLOW



Photographs by C. N. Fenner, 1919

TREE NEAR THE SANDFLOW, WHOSE UPPER TRUNK HAS BEEN BURNT shelf and appear to be an intercalated deposit, while actually only a thin veneer clinging to the walls. The matter needs further investigation.

A case in which there seems no doubt of two sandflows separated by Katmai ash is to be seen on the southeastern side of Katmai Pass, along the flats of Mageik Creek. The relations are shown in the accompanying sketch. The bottom of the deposit is not exposed, but from the stream level up there is a thickness of 40–50 feet of typical unstratified sandflow material of a light-buff color, then comes 4 ± feet of gray, stratified ash and pumice, interpreted as representing the Katmai ashfall, and again 20–30 feet of unstratified tuff similar to that below. The upper and lower deposits are perfectly distinct from the intercalated strata of Katmai ash.



Section of the sandflow along Mageik Creek, divided into two portions by the Katmai ashfall.

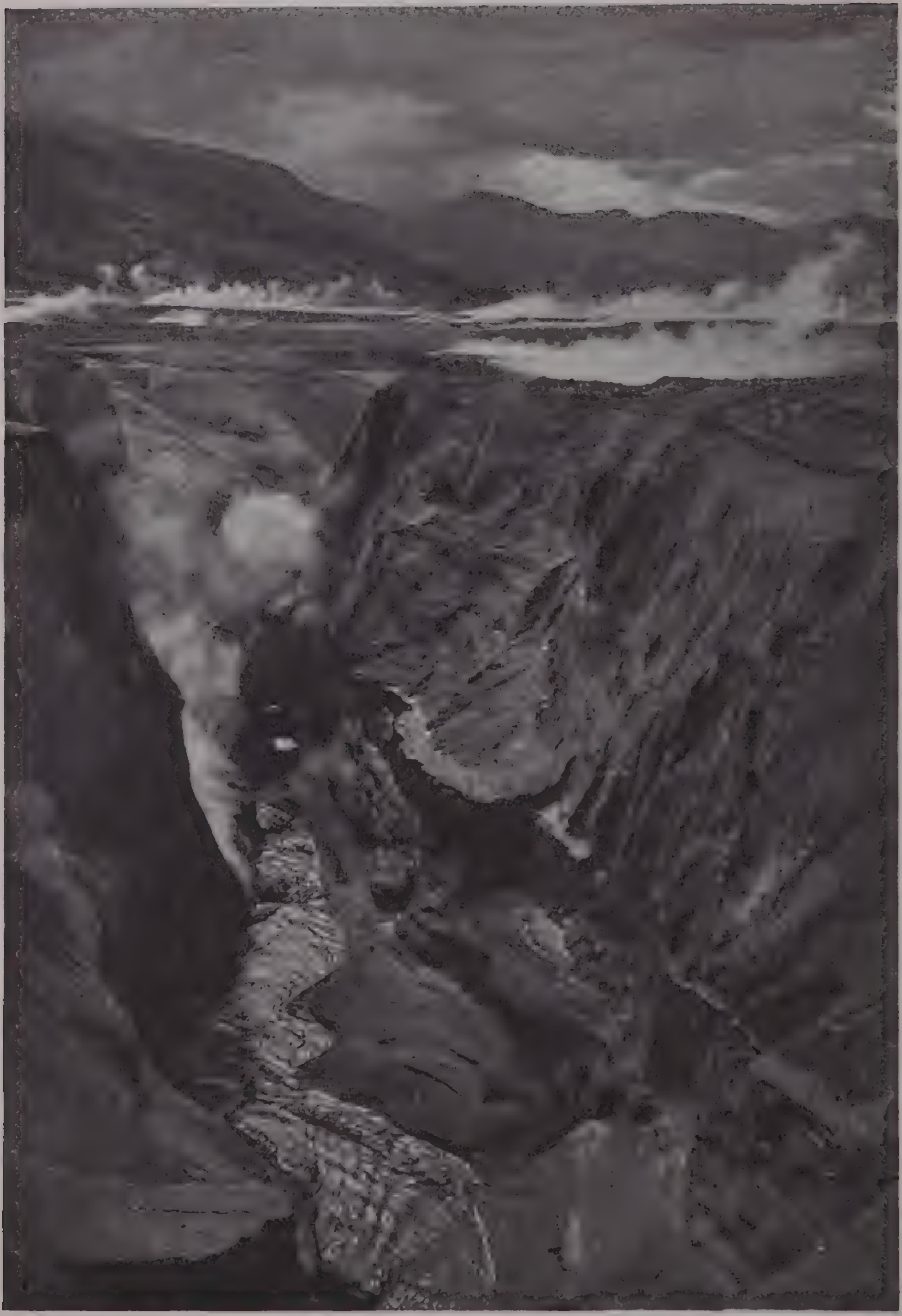
EVIDENCE AS TO THE PROBABLE THICKNESS OF THE TUFF DEPOSIT

Many of the essential characteristics of the tuff have been described incidentally in what precedes, but others of importance have not been mentioned.

As one looks across the Valley of Ten Thousand Smokes, he sees what appears at first, from a topographic point of view, an almost featureless plane surface sloping gently and uniformly from southeast to northwest. The striking phenomena presented by the vapors from innumerable fumaroles are not here considered, and apart from these the Valley would seem like a monotonous dun-colored desert. The eye might be caught by the high sand mark which bounds much of the area, and one might notice that in many places there is a slight but perceptible slope from the sides toward the middle.

The stream canyons would hardly be observed except on close approach, but are remarkable features. The two main streams, in the upper parts of their courses, are not sunk much below the general level, but as they flow down the Valley their trenches become deeper and deeper, and in places the walls are probably nearly 100 feet high, entirely in tuff, firm enough to stand almost vertical (see pages 32 and 34).

There is little to indicate what the maximum depth of the tuff may be. At Three Forks a thickness of 50–60 feet is exposed, resting



Photograph by Frank I. Jones, 1919

KNIFE CREEK CANYON

A portion of one of the narrow gashes cut in the sandflow by streams since its deposition.

on boulder till, but this section is in the lower part of the Valley and near the western side, where it would naturally be comparatively thin. Above this point erosion has nowhere shown the bottom. Some hint, however, is afforded by the description of the former appearance of the Valley as seen by J. E. Spurr [1] during his journey through it in 1898. Speaking of the upper part of the Valley (southern arm) and the adjacent mountains, he says:

> Along the axis of the mountains are large and well-developed glaciers, especially on the sides of a tall volcano [Mount Mageik] which stands directly at the head of the valley up which the trail runs. Here the glaciers are many and distinct and have splendid moraines. The main valley is filled with horizontally stratified sand, in which are great angular boulders, which are also beautifully arranged in layers. This deposit has a generally level top, but there are many sharp hillocks formed of bunches of huge boulders. The streams have cut deep channels through this. . . .
>
> The valleys of the streams which drain both sides of the pass [Katmai Pass] are deeply excavated, especially that on the northwestern side, which has cut down at least 100 feet through lava boulders. Owing to the excessive frost action, the whole surface of the volcanoes is covered thickly with these large boulders. On the northwestern side, near the summit, a lake half a mile long is dammed by the débris from three volcanoes which rise above it.[2] . . .
>
> All along the valley leading to the pass are stratified gravels, which near the beginning of the trail across the pass begin to be filled with great angular boulders; these are, however, beautifully layered. Dotting the level are many sharp hillocks formed of huge striated boulders, evidently dumps of icebergs.[3] This deposit runs quite up to the foot of the existing glaciers, there being no unmodified drift except recently abandoned moraines.[4]

All this topography of the Valley floor, with its moraines, stream gulches, lake, and glacial dumps, has now entirely disappeared. When we consider the sort of valley that Spurr's description pictures to us, as contrasted with the present even surface of the tuff deposit, it seems indeed quite probable that in the upper Valley the tuff may attain a depth of several hundred feet in places. We must, moreover, take into account the fact that not only has the former topography been buried, but also that a great avalanche of rock seems to have been precipitated from the face of Falling Mountain down into the Valley just prior to the eruption,

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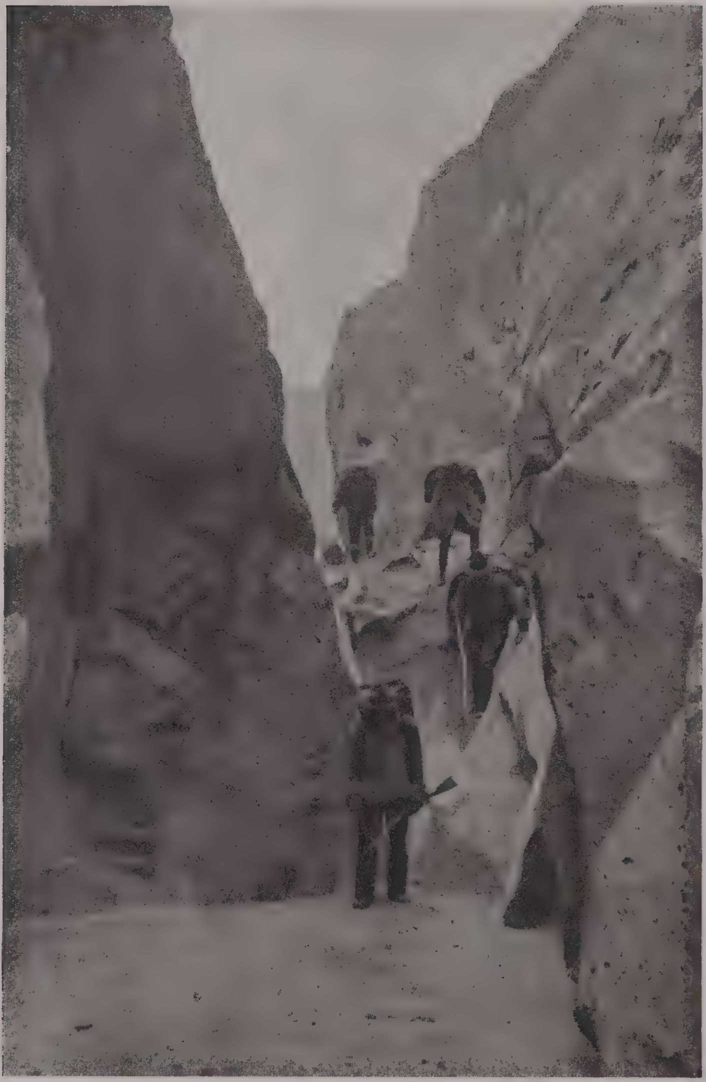
[1] Spurr, J. E., A Reconnaissance in Southwestern Alaska in 1898: U.S. Geol. Survey. Twentieth Ann. Rept., pt. 7, pp. 31–264.

[2] Op. cit., pp. 146 and 147.

[3] Spurr's mention of icebergs relates to his belief that the valleys of this region had been depressed beneath sea-level and that the glaciers, during their maximum expansion, were little larger than at present. In 1919 I found glacial erratics on the western side of the large open valley of Katmai River to a height of nearly 2000 feet above the floor, and many other evidences of former much more vigorous glaciation.

[4] Op. cit., p. 255.



Photograph by R. F. Griggs, 1919

CANYON OF THE RIVER LETHE

The walls of such canyons are nearly 100 feet high in places, entirely of sandflow material whose base is not visible. During a portion of the year they carry no water.

and to have been so nearly buried by the sandflow that little or no trace of it is to be seen.[1]

There are, however, two marginal features of the Valley in this vicinity (Novarupta basin) whose present form may be influenced by the old topography. It has been mentioned that at Baked Mountain the high sand mark is a terrace-like feature elevated considerably above the general level. This suggests that there may formerly have been a terrace of glacial origin here, on which the present high sand deposit is perched, as it were. The second feature is the ridge near Novarupta which separates Novarupta basin on the west from the head of the southeastern arm on the east, and which, it was seen, would have acted as a dam to a mudflow or sandflow from Katmai. The position and rounded form of this ridge suggest that it may be an old moraine, covered now by the Novarupta deposits.

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[1] No trace of this avalanche is now visible in Novarupta basin, except a few conical mounds of rock, reaching a maximum height of 40 to 50 feet, one of which is shown on page 52. Even these may be parts of another fall occurring after the sandflow.

THE MAKE-UP OF THE TUFF DEPOSIT

In the lower part of the Valley of Ten Thousand Smokes there are many places where recent erosion has exposed sections of tuff which are well suited for a study of the make-up of the deposit. Such sections are found to show an essentially uniform mass, consisting of a matrix of fine-grained "ash," in which are set pieces of pumice from minute size up to 4 inches or more in diameter, generally white but also black, striped, or gray; fragments of dense black obsidian, of dark and light andesites, and of shale and sandstone. There are indistinct lines or bands of stratification, up to a foot or more in width, often running 50 feet without losing their identity, distinguished by a greater proportion of coarse pumice.[1] The occasional flat bits of reddish shale scattered throughout have a tendency to lie horizontally. The general color of the whole mass is pinkish-buff.

A sample of the material of the tuff deposit taken near its northern margin and not far from Ukak Camp, has been found to be made up as follows:

(a) Material passing 200-mesh sieve (sieve openings 0.0029 inch or 0.074 millimeter), 82.2 grams—34.46 per cent of the whole. Is almost wholly made up of angular fragments of colorless glass of index 1.493, but a few dark specks (dark pumice and lapilli) are visible; phenocrysts are very rare.

(b) 200-100 mesh (0.074–0.147 mm.), 37.8 grams—15.85 per cent; mostly colorless glass (fragments of pumice); a few dark specks (dark pumice and lapilli) and a few phenocrysts (feldspar, pyroxene and magnetite) are found.

(c) 100-48 mesh (0.147–0.295 mm.), 28.8 grams—12.07 per cent; mostly colorless fragments of glassy pumice, but with a little dark pumice and dark lapilli; a few phenocrysts.

(d) 48-35 mesh (0.295–0.417 mm.), 12.7 grams—5.32 per cent; mostly fragments of light-colored pumice, but some dark pumice and lapilli; a sprinkling of phenocrysts.

(e) 35-28 mesh (0.417–0.589 mm.), 10.0 grams—4.19 per cent; mostly light pumice; also dark pumice, lapilli, and a sprinkling of phenocrysts.

(f) 28-20 mesh (0.589–0.833 mm.), 12.4 grams—5.20 per cent;

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[1] At St. Vincent "the vertical sections of the new ash did not show any very distinct stratification." Anderson and Flett, op. cit., p. 432.

mostly light pumice; also dark pumice, lapilli, and a sprinkling of phenocrysts (including quartz).

(g) 20-10 mesh (0.883–1.651 mm.), 19.9 grams—8.34 per cent; mostly light pumice; also dark pumice, lapilli, and fairly numerous phenocrysts.

(h) Greater than 10 mesh (greater than 1.651 mm.); includes
(1) light-colored pumice, 24.5 grams—10.27 per cent,
(2) dark-colored pumice and bits of old lavas, 9.2 grams—3.86 per cent,
(3) bits of shale and sandstone, 1.0 gram—0.42 per cent.

Total, 238.5 grams.

In this separation material finer than 35 mesh (less than 0.417 mm.) is considered a fine sand; this comprises 67.70 per cent of the whole; material between 35 and 10 mesh (0.417–1.651 mm.) is a rather coarse sand and forms 17.73 per cent; material larger than 10 mesh (larger than 1.651 mm.) is a gravel; this forms only 14.57 per cent.

This description applies with little modification to the tuff deposit over the whole area of the lower Valley wherever sections are exposed, though in walking over the surface one gets an impression that the relative proportions of the component materials vary somewhat. In places the amount of sedimentary fragments increases; in others the black and dark-colored pumice is in relatively greater amount as compared with the white.

The bits of shale and sandstone in the tuff bear evidence of having been exposed to heat. The color of the Naknek sediments which underlie the Valley and form the hills and mountains outside of the volcanic range, is generally of a somber green or greenish-gray. The fragments included in the tuff are almost always reddened or blackened if of shale, and reddened or whitened if of sandstone. At times thin crusts of pumice adhere to them. The general pumice of the deposit is nearly white, but dark or banded specimens are numerous.

As one goes up the Valley the tuff deposit shows a tendency to become a little coarser in grain and the buff color takes on a grayer tone, but the difference is generally not marked. At one place, however, a decided difference appeared. This was at the mouth of the large gulch that enters the Valley from the west side of Knife Peak. The deposit here is cut by a stream, and the material shown is of a dark purplish-brown. This applies both to the fine material and to most of the lumps of pumice, which, up to the size of one's fist, are liberally sprinkled throughout, but there is also white pumice, and pieces in which the two contrasted kinds are associated in the same specimen.[1]

In the upper branches of the Valley deep trenching by streams is absent, and in most places the ejecta from Katmai and Novarupta conceal the underlying sandflow. In Novarupta basin especially the relations are complicated. I feel that an intensive study of the deposits here would bring to light considerable additional information regarding the processes at work during the eruption.

At a place about halfway between Camp 5 and Novarupta (in the vicinity of fumaroles 123 and 111) the walls of a wide, fairly deep gully show a section of which the upper 30 feet consists principally of a light-colored pumice (in pieces 3–6 inches in diameter), mingled with gray, dark, and variegated pumice, small pieces (walnut size) of black, stony lavas, of obsidians, and of burnt shale. With these there is but little fine material, and the whole is quite loose. A stratification is visible when one looks along the section, and these strata are believed to represent the later ejecta from Novarupta. There is very little variation in character from top to bottom, but underneath there is an abrupt change to a quite different deposit.

The color of the latter, instead of being a light-gray, is a dark-brown, due both to the darker color of the fine matrix present and also to the prevailingly dark-colored coarse material. It is quite firmly cemented. The coarse lumps are of various kinds — both light-colored and very dark pumice, black obsidian, semi-obsidian (pore-filled glass), basic andesites (some partly melted and in a state of transition to a black pumice), obsidians made up of a glass matrix carrying angular inclusions of various kinds, and bread-crust bombs.

In contradistinction to the medium-grained material in the overlying strata, the lumps in the lower deposit are frequently 2 feet in diameter. Unfortunately, the lower deposit is exposed to a depth of only about 4 feet, so that the above description applies only to this. My view is that the lowermost deposit probably represents the sandflow near one of its principal points of extrusion, but the small thickness of the exposure leaves the matter somewhat uncertain.

In going eastward along this gully toward Novarupta, the character of the upper deposit changes. The size of the pumice blocks rapidly increases so that at one-half mile from Novarupta blocks of one foot or even two feet in diameter are not uncommon, and the color becomes much darker.

[1] In a sample of this material that was brought home and has become dry the fine portion appears much lighter than when in situ. When it is put into a liquid of index 1.545 it becomes nearly black, but has numerous nearly white particles scattered through it. Large lumps in the dry sample still appear black, white, and banded.

As has been seen from the description, the bulk of the material of the sandflow is light-colored pumice or fragmental glass, the latter often shattered to a fine dust. The index of refraction as determined by the immersion method is approximately 1.490. This nearly white pumice carries a little quartz and acid plagioclase as practically the only phenocrysts. The dark pumice has an index of about 1.535 and carries basic plagioclase, augite, hypersthene, and magnetite, at times in abundance.[1]

These two sorts of pumice are often in perfectly distinct pieces, but a large number of specimens were found in which partial mingling has produced curious banding, one example of which is shown on page 39. Further mixture results in a homogeneous pumice of intermediate composition.

It requires little study of these banded pumices to produce a conviction that they were formed by the partial mingling of two chemically diverse fluids. A clue to the explanation is to be found in the structure of the lava of the Novarupta dome and the nature of the ejecta from this source, which will be described a little later.

Before this evidence is presented, however, it may be said to indicate very strongly that dark-colored rocks of basic composition were partly or wholly melted by the new siliceous magma, and that imperfect mixture produced the banded rocks. The variation mentioned in the proportions of white and black pumice, and in the relative amount of older rocks — lavas and sediments — to the pumice, in different parts of the Valley is consistent with the conclusion arrived at from other reasoning that the material of the tuff deposit was extruded from a number of vents, and thus local modifications of composition resulted. The probable situation of these will now be considered.

POSSIBLE VENTS OF EXTRUSION OUTSIDE THE VALLEY

Katmai Crater was rejected, for what seemed to us compelling reasons, as a source of the material of the tuff deposit, and the slopes of the surrounding mountains appear in most places so devoid of recent volcanic or fumarolic activity as to make it seem very unlikely that orifices of extrusion were situated upon them.

An exception must be made, however, in regard to the slopes of Mount Trident to the southeast of Novarupta. For a distance of nearly two miles from Novarupta in this direction (which brings us well up on the slopes of Trident) the thick deposits of pumice cov-

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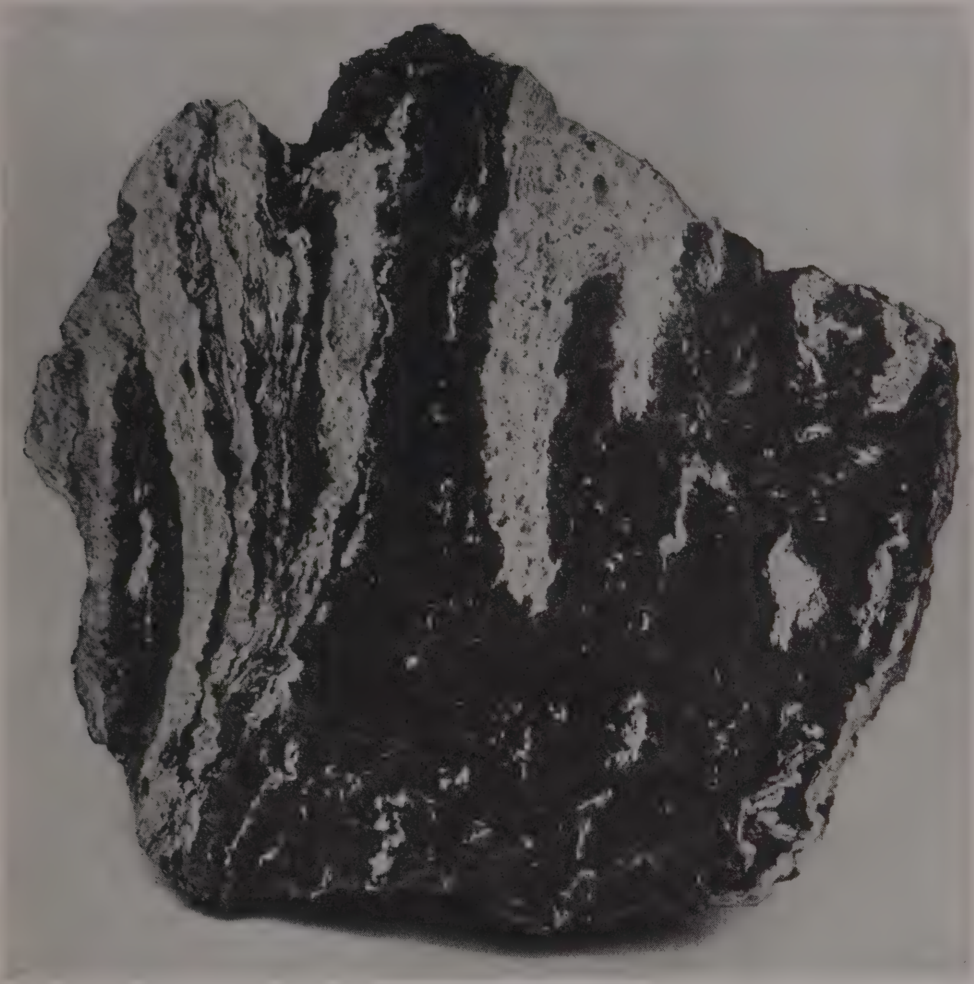
[1] A more detailed petrographic description of the erupted materials will be given in another article.



SPECIMEN OF BANDED PUMICE FROM THE VALLEY OF TEN THOUSAND SMOKES

The structure is believed to be due to a melting and partial mixing of old basic rocks in the new siliceous magma (size 4 x 4 inches).

ering the surface are cut by numerous large fissures, along which fumaroles are situated. These fissures seem likely sources for a portion of the tuff (see page 14).

It seems possible, too, that there may have been orifices on the southern slopes of Trident's westernmost peak which acted as sources for some of the material in Katmai Pass and in the valley of Mageik Creek. These mountain slopes have not been sufficiently examined to demonstrate this point; it is suggested by the fact that the fumarolic activity near the summit of the pass was not vigorous even when the region was first discovered,[1] and in 1919 appeared very

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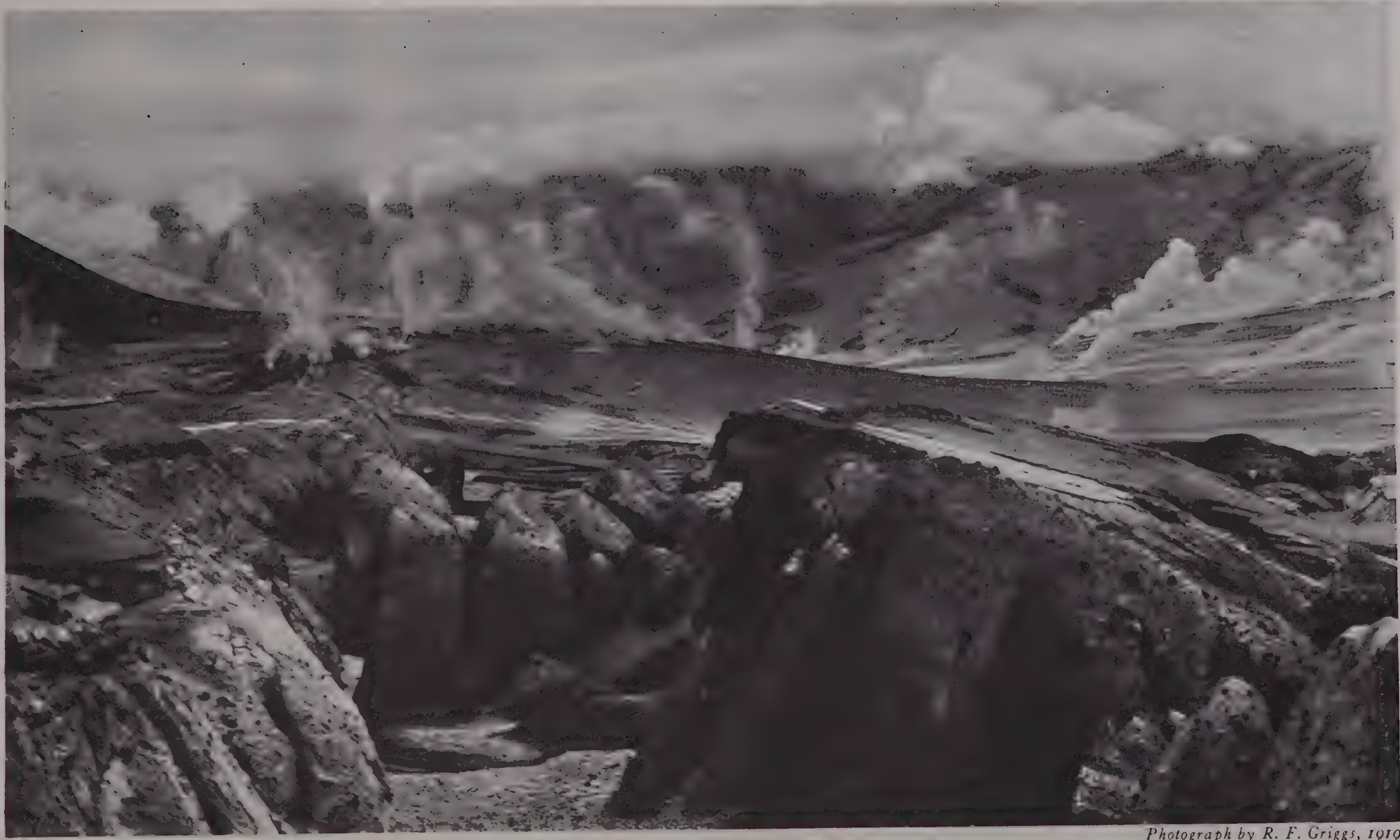
[1] Griggs, R. F., Nat. Geog. Mag., vol. 31, p. 63, 1917.



Photograph by R. F. Griggs, 1919

A LONG LINE OF FUMAROLES ALONG A FISSURE AT THE HEAD OF THE SOUTHERN BRANCH OF THE VALLEY feeble. The fissures here were not impressive, and one is disposed to look for a larger orifice for the material that flowed down Mageik Creek.

Except for these possible sources on the slopes of Trident, no other points beyond the margins of the tuff deposit seem likely sources, and one must inquire what possibilities the Valley itself offers.

CHARACTER OF THE FISSURES IN THE VALLEY

On the accompanying map (pages 4 and 5) the positions of numerous fumaroles are shown, but these are merely the ones that have been studied, and represent a very small fraction of the whole number. In the arrangement of these mapped fumaroles no idea is conveyed of the great lines of fissures that intersect the surface. Below Three Forks there are only two important fumaroles (1 and 2), and above this point there are fairly wide areas, probably reaching two or three square miles, where no signs of activity are to be seen, but the general surface is well sprinkled with vents and in many areas they are exceedingly numerous.

Openings may occur singly or in groups, and in the latter case not only are there many fumaroles of different sizes, but the whole surface of the soil is likely to leak steam. Often they are plainly distributed along fissures. The latter relation is best observed when one is on a height from which a comprehensive survey of the distribution may be had. Naturally the fissures are not open in a continuous line to a great depth, but the cracks are plainly visible. Along such a fissure vapors may rise from numerous openings for half a mile or more, or fumaroles may occur at greater intervals. Page 40 shows one of these long lines of vents.

The nature of the gases and sublimates evolved from these vents has been studied in detail by Allen and Zies.[1] Water is always a prominent constituent of the gases and in places almost the only one, but usually they contain in addition hydrochloric and hydrofluoric acids, sulfur acids, carbon compounds, hydrogen, nitrogen, and argon. In the crusts sulfur is found deposited in considerable masses, as well as large amounts of ferric oxide. Pyrite and magnetite in fresh crystals also occur, as well as opaline silica, ammonium chloride, and a long list of minor constituents, among which are a number of the heavy metals. The temperatures range as high as 645° c.

An important point to be noted is that the fissures are almost absolutely restricted to the Valley area, including in this term Baked Mountain, Broken Mountain, and Falling Mountain, which the Valley practically surrounds. The fissures on the lower slopes of Trident

[1] The second memoir of this series, now in press.

are outside of it, strictly speaking, but are immediately adjacent on the side toward the volcanic range, which may be supposed to mark a profound break which has served as a volcanic outlet for many thousand years and which may have acted as the supply conduit for the outbreaks in the Valley.

In the lower part of the Valley, which was the area first studied during the summer of 1919, the fact that the fumaroles and fissures are not to be found outside of the tuff filling caused us to wonder for a time if they were superficial phenomena and if the hot vapors and sublimates arose simply from the mass of tuff. Certain observations seemed to point in that direction. Small fumarolic vents were found, marked by bright-colored iron deposits cementing the material of small mounds, which seemed to have been temporary affairs and were perfectly cold. A number of these occur in Ukak Valley, northwest of fumaroles 1 and 2, and others were found in the vicinity of Ukak Camp, in embayments of the shore line of the tuff deposit, where there was nothing to indicate fissuring.

Even later, when we studied the plentiful evidence of deep fissuring in the upper Valley, in fact up to the present time, we have continued to believe that some of the weaker fumaroles may have had no deep-seated source, but that they were due to gas given off by the body of tuff. As to whether any of the fumaroles still active in 1919 were of such origin, we have no means of deciding.

In the southern arm of the upper Valley marginal fissures and fumaroles are found at a number of places on the western side at about the height of the high sand mark. Some of these, although situated within the tuff area, are so near the margin that the depth of tuff can hardly be more than a few feet, and their emanations can not be supposed to have their source in this. Their position is ascribed to the fact that beyond this limit fracturing would have had to rupture the increasingly thick masses of rock strata of the adjacent mountains, and it was not competent to effect this.

On the westward-facing cliffs of Baked Mountain, near our camp, a few fumaroles emanated from cracks in the solid rock at a considerable height above the valley floor, and these could not be ascribed to any deposit of tuff or pumice, but the best examples of deeply penetrating fissures outside of the tuff were to be found on Broken Mountain and on the northerly face of Falling Mountain.

The latter is a precipitous, scarred slope which gives the impression on even casual inspection that a great slice of the mountain has recently dropped off into the Valley below (see page 44). This must have occurred prior to the eruption, for it has been covered by the sandflow. The rock of the cliff appears badly shattered. From the time that it was discovered until we saw it in 1919, it has continued to send down boulders which have accumulated in large talus slopes, but these piles do not begin to fill out the original contours of the mountain. Quantities of vapors rise from crevices in the broken face, and close to the intersection of the slopes with the tuff deposit there are large steaming fissures and crater-like openings.

Immediately to the north of Novarupta rises Broken Mountain, whose name was applied because of its innumerable fissures. It seems literally true that much of the mountain was fractured into small blocks (see page 46). The surface is covered with a thick deposit of ejecta from Novarupta, so that bedrock is not visible, but the width, height, and general nature of the fissures indicate fundamental fractures, rather than any sort of slumping in the pumice deposits. Moreover, many of them show marked displacements of the two opposite sides, as shown in the accompanying sketch. Fumarolic activity along these fissures was pronounced, and one is forcibly impressed by the choking emanations.

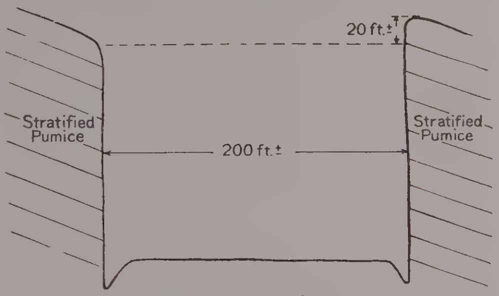


Diagram of fault on pumice-covered slopes of Broken Mountain. Probable displacement 75–100 feet.

MOST OF THE FUMAROLES FROM DEEP-SEATED SOURCES

The characteristics of most of the fissures in the Valley tuff, as has been described — their length, the long persistence of fumarolic activity, the high temperature of the issuing gases, the nature of the emanations — indicate that they can hardly be superficial phenomena originating in the tuff itself, but that they continue to depths where there is a fairly direct connection with molten or recently consolidated rock.

Knowledge that the bedrock of Falling Mountain and Broken Mountain is fractured in a similar pattern gives additional confidence in a belief in the fundamental character of the openings throughout the whole Valley area and disposes us favorably toward the idea that the fissures were orifices of extrusion for the tuff deposit.

Lacroix has given good reasons for believing that the fumaroles in the tuff deposits resulting from the nuées ardentes of Mount Pelée were almost wholly of superficial character,[1] basing his conclusions

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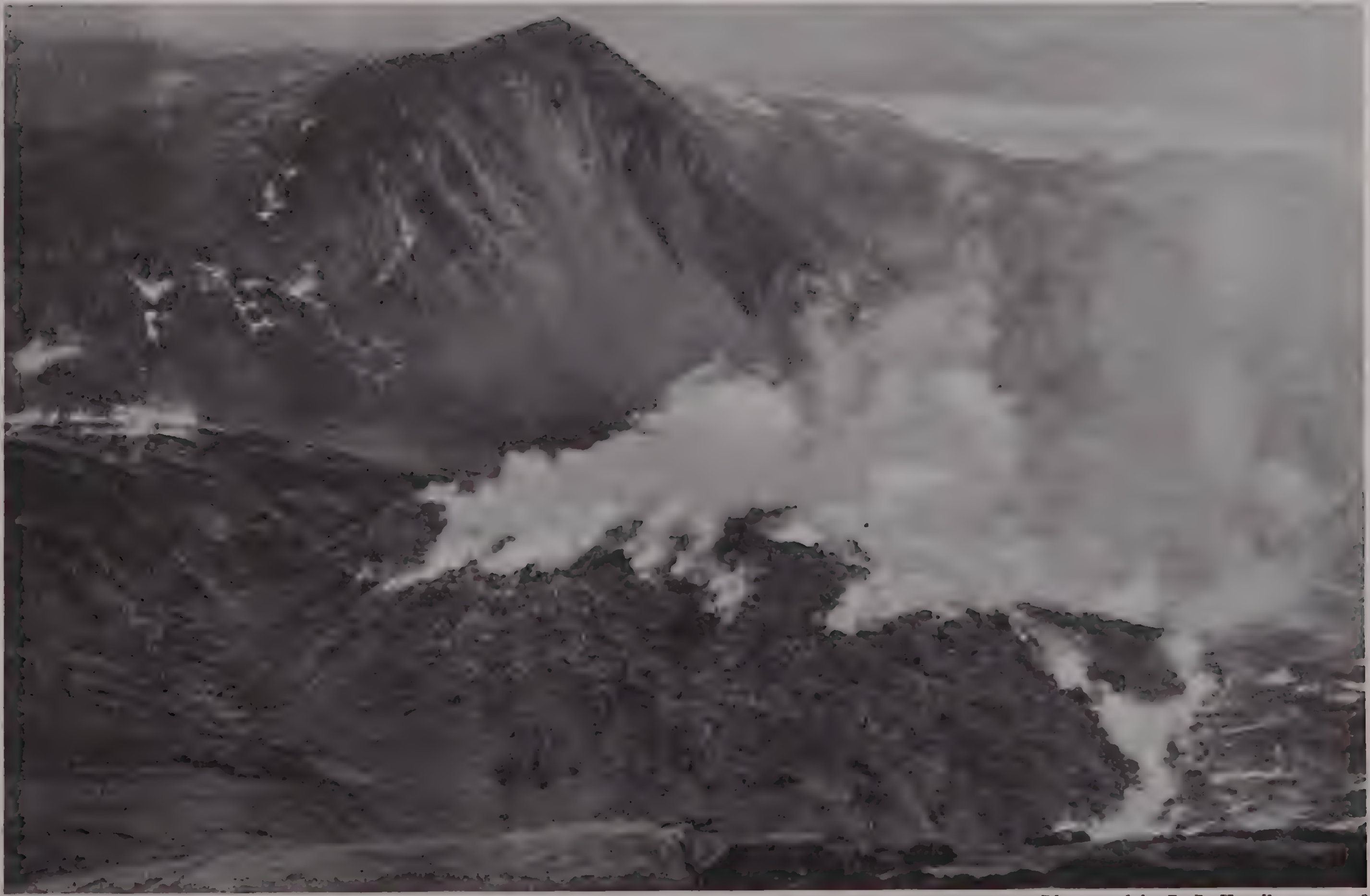
[1] La Montagne Pelée et Ses Éruptions, p. 391.



Photograph by P. R. Hagelbarger, 1918.

NOVARUPTA AND FALLING MOUNTAIN, AS SEEN FROM THE NORTHERN RIM OF NOVARPUTA on the important facts that he was nowhere able to find traces of fissures in areas from which erosion had removed the tuff; that some of the fumaroles were in close association with colossal blocks of dense rock at a high temperature, such as were carried along in abundance; and that the chemical action associated with the fumaroles was relatively feeble.

In the Valley of Ten Thousand Smokes the antithesis of these conditions holds as nearly as possible, as has been explained in detail, and there seems abundant reason to believe that most of the fumaroles are connected with deep-seated sources.

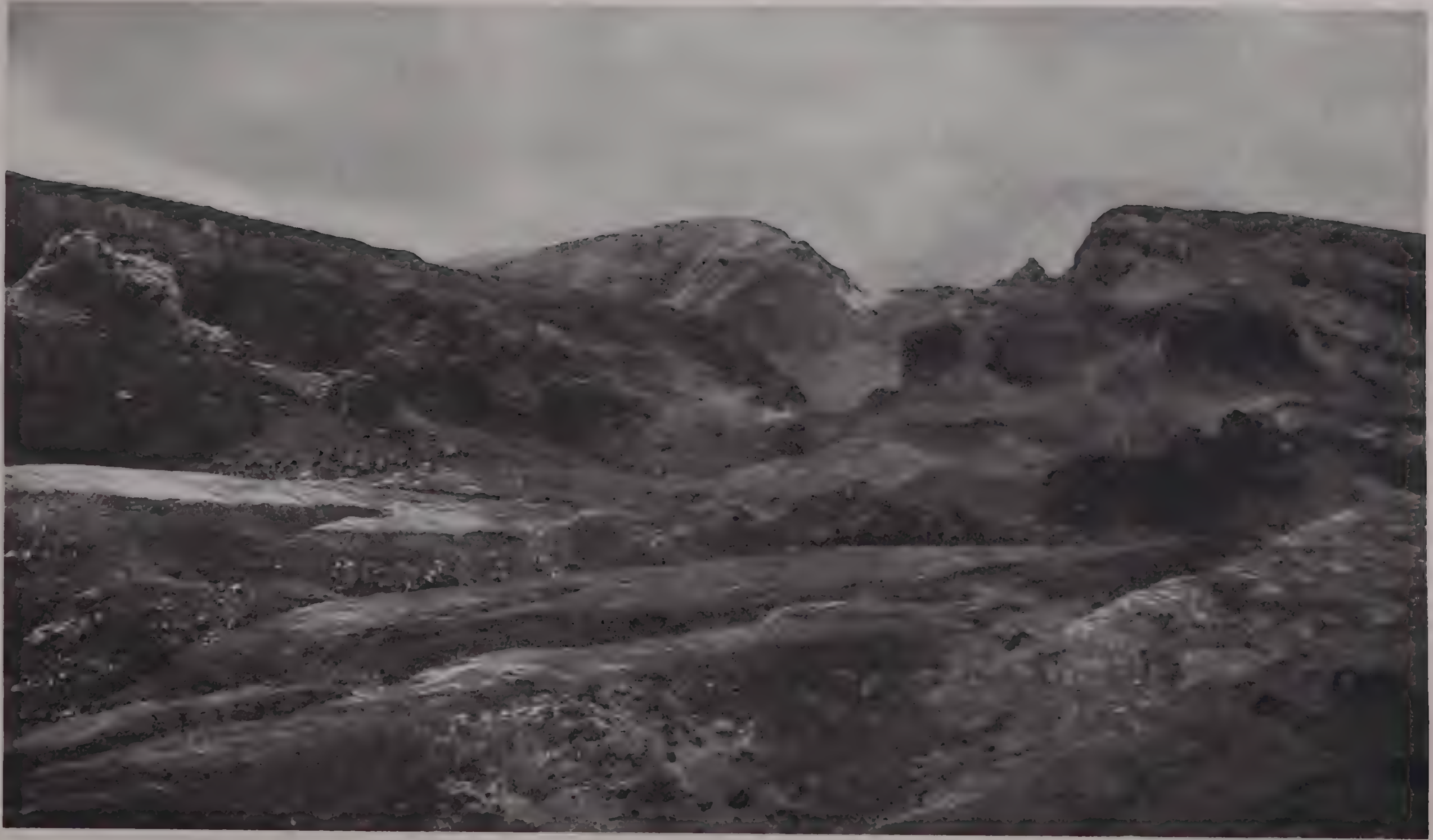
In some cases the orifices of the fumaroles do not project above the general surface, but in others we find them surrounded by gently sloping mounds. Fissures, too, are often marked by a distinct ridge (see pages 40 and 68).

In the southeastern arm of the Valley especially we find numerous deep craters, either singly or distributed along fissures, whose rims are decidedly raised (see page 70). In a typical example there was a series of craters with intersecting rims situated along an axis running north 60° east. Steam and crustification were general, though no open fissure was visible. The craters had a very well developed bowl-like form and had a maximum depth of probably 40 feet. The axis along which they were situated formed a ridge well above the surrounding country and extended for a long distance.

In numerous places in the southeastern arm we found examples of similar craters. One was a pit of probably 100–150 feet diameter, with a steeply sloping funnel-like interior. Clouds of steam were coming out, apparently from the bottom. The outer rim was distinctly raised, sloping away on all sides, and there was a very decided increase in the amount of coarse pumice on these outer slopes. Most of this pumice was nearly white, but black and variegated pieces were not uncommon, together with dense black glass with xenoliths.

In one case the height of the rim above the general surroundings was estimated to be 15–20 feet. Craters believed to be 200 feet in diameter and 75 feet deep were found. Some of these openings may possibly be due to secondary explosions or to short-lived ejections from the tuff itself, but those situated along lines of fissuring or which show fumarolic deposits or were still active when we saw them are probably of deeper origin.

Mention has been made of the striking fact that the fissures are confined almost exclusively to the area of the Valley. Throughout this irregularly shaped depression, for a distance extending to a maximum of 16 miles from Katmai Crater, they have broken through almost



Photograph by P. R. Hagelbarger, 1918

BROKEN AND FAULTED COUNTRY ON THE UPPER RIM OF NOVARUPTA (SOUTHERN END OF BROKEN MOUNTAIN) everywhere. From their orifices the pumiceous material that formed the tuff deposit seems to have been expelled, and their present emanations indicate connection with a body of magma below.

HYPOTHESES AS TO THE MAGMA BODY

What is the reason for this distribution and what is the form of the body of magma? I have drawn the inference that the forces producing the fissuring were not located at profound depths, but so near the surface that the thinness of strata of the Valley area as compared with that of the adjacent mountains was a decisive factor, and that such a set of phenomena would be expected if a sill of magma were driven like a wedge by hydrostatic pressure between the nearly horizontal strata of shale and sandstone underlying the Valley.

As to the depth of intrusion that would determine whether the valley floor alone or the floor and mountains both should yield, a solution of the problem in quantitative terms is hardly possible because of uncertain data and complicating factors; but it may probably be stated in a general way that if the strata overlying the sill were so thin that less pressure would be required to overcome their breaking strength than to lift the excess weight of rock of the mountain mass, fracturing would be confined to the valley.

We observe that while the thick masses of rock at the sides of the Valley were not fractured, the thinner but still very considerable masses that form Broken Mountain, Falling Mountain, and the lower slopes of Trident were greatly shattered, and we infer that the depth of intrusion was considerable (possibly several thousand feet) but yet not profound.[1]

This conception I would not urge as more than a hypothesis, but it seems to me more in harmony with observed facts than either of two other possibilities that might be suggested; namely, a series of approximately vertical fissures rising from profound depths; or the breaking-up of the roof over a great batholith.

As regards the former, profound fissuring would hardly be expected to pay so much attention to such a surface feature as the Valley, nor to produce such a net-like fragmentation without definite trends as we seem to have.[2]

The second hypothesis would meet other difficulties. If the break-up of the roof over a great batholith should occur, the volcanic forces

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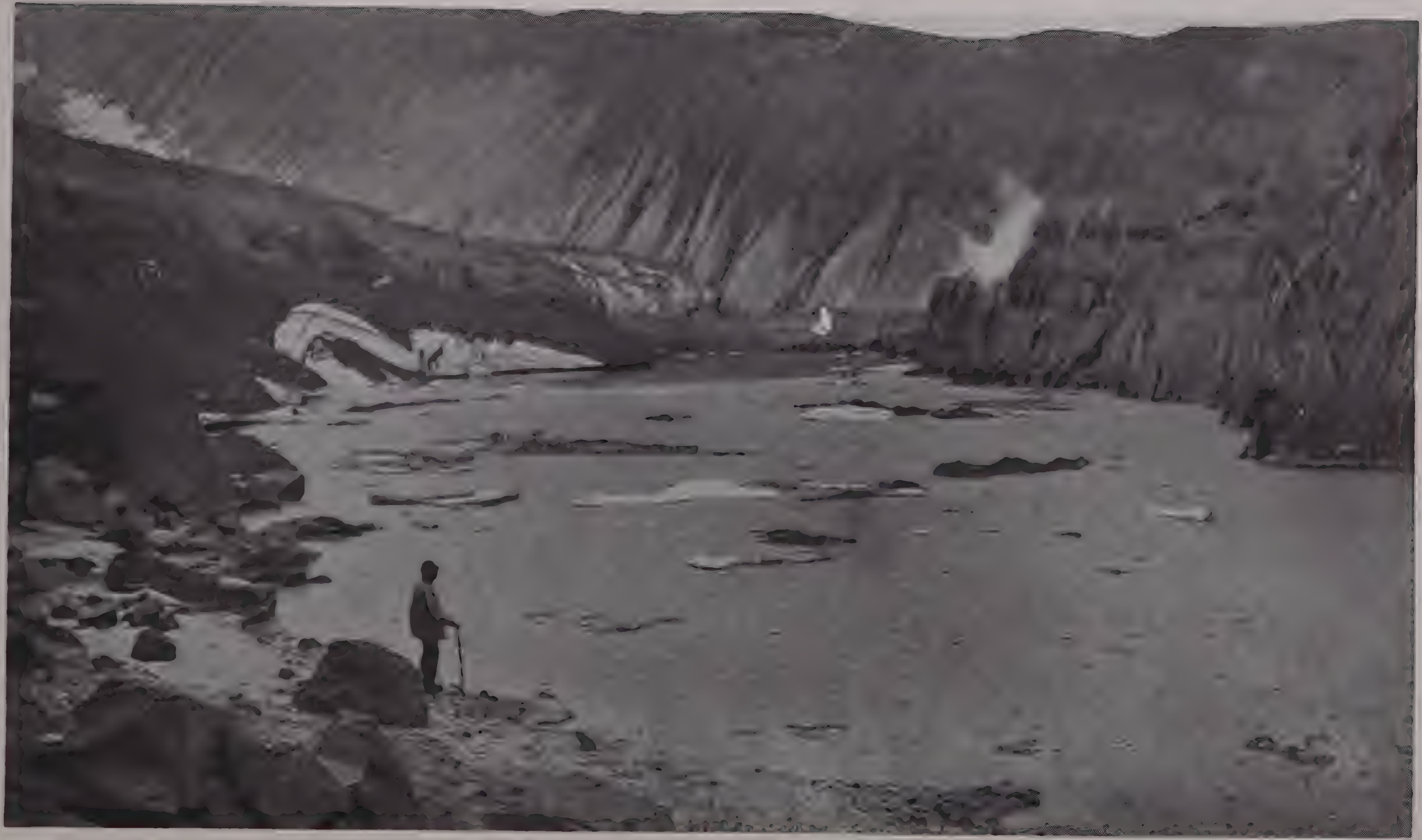
[1] The magma that was drained off at this lower level and that broke out through the floor of the Valley seems to have been of the same composition as that which rose into Katmai Crater.

[2] The pattern of the fissures appears no more orderly than that of blocks of ice broken by a rise of water beneath. It would be helpful, however, if the principal lines of fissuring had been surveyed and mapped.



Photograph by J. W. Shipley, 1917

FISSURE LAKE, AT THE MARGIN OF THE SANDFLOW AND AT THE FOOT OF THE GLACIERS OF MOUNT MAGEIK would seem to be offered all freedom of escape that could possibly be required, and the great climax should have resulted here rather than in the crater of Katmai.

It might be urged in opposition to the hypothesis of either a sill or vertical dikes that dike-like intrusions of rhyolite are rather rare, while granitic batholiths are common; nevertheless dikes of rhyolite are found frequently enough so that this would have little weight,[1] and on the other hand granitic batholiths of the extreme composition that the Katmai magma seems to have had before it became mixed with other material near the surface are very unusual.[2]

There is a little indication that in 1919 the sill supposed to underlie the Valley was undergoing fracture as it cooled. Several times members of our party heard subterranean sounds loud enough to be quite noticeable. In each case there was a sharply defined report, very similar (though on a much larger scale) to that which a specimen of hard rock gives when it is suddenly broken. Moreover, in one area at least (near fumarole 144), the hard crusts which, in places, bridged the lines of long fissures gave indications of recent fractures and slight displacements.

ANALOGOUS INTRUSIONS ELSEWHERE

The form of intrusion suggested here is one that would occur only under special conditions, and its surface expression would not survive for a long period, but I have seen one region where the same sort of process is indicated. This is in Shasta Valley, California, and does not seem to have been studied in detail. The only literature that I have found relating to the area is Bulletin 614 of the U. S. Geological Survey,[3] which says:

> Scattered over Shasta Valley are many small knolls of lava and tuff, which appear to be, in part at least, the products of minor and local eruptions that broke through the Cretaceous beds, each vent contributing its little pile of material. Such feeble and diffuse volcanic activity is in marked contrast with the vigorous outbursts that built up the great cone of Shasta.

This brief description hardly gives an adequate picture of the remarkable appearance of the cones. The railroad traverses this broad valley for a distance of 25 miles or more, and the cones rise, probably in hundreds, directly from its flat floor. Most are symmetrical, but some are quite irregular. The height varies from a few feet to several hundred. The lava composing them is black and very scoriaceous. At the southeastern end the valley is blocked by the great cone of Mount Shasta, which thus bears a relation to the vents very similar to the relation that Mount Katmai bears to those in the Valley of Ten Thousand Smokes.

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[1] See, for example, Geikie, A., Text-book of Geology, vol. 1, p. 213, New York, 1903.

[2] The matter of the melting-down and digestion of foreign material during the Katmai eruptions will form the subject of a separate article, but a little of the evidence, drawn principally from Novarupta, will be presented later in this paper.

[3] Diller, J. S., and others, Guidebook of the Western United States, Part D; The Shasta Route and Coast Line, p. 61: U. S. Geol. Survey Bull. 614.

The fact that the extruded lava built up cones here, while in the Katmai region it formed a great sandflow, would appear to be due to the basic composition and relatively gas-free condition of one and the siliceous composition and highly gas-charged condition of the other.

Geikie[1] cites examples of the lifting power of injected magmas among the ancient volcanoes of Britain.

> In the deeper portions of a volcanic vent the convulsive efforts of the lava column to force its way upward must often produce lateral as well as vertical rifts, and into these the molten material will rush, exerting as it goes an enormous upward pressure on the mass of rock overlying it. At a modern volcano these subterranean manifestations cannot be seen, but among the volcanoes of Tertiary and older times they have been revealed by the progress of denudation. Some of these older examples teach us the prodigious upheaving power of the sheets of molten rock intruded between volcanic or other strata.[1] . . .
>
> That these later manifestations of volcanic energy have sometimes taken place on a great scale is shown by the number and size of the sills which are found at the base of the Paleozoic volcanic groups of Britain, where this feature of volcanic action has been especially investigated. Thus the great Cambrian and Lower Silurian volcanic outflows of Arenig and Cader Idris in North Wales are underlain with a profusion of basic sills. The same structure reappears so markedly among the volcanic groups of the later Paleozoic formations, and also in those of Tertiary age, that it must be regarded as marking an ordinary phase of volcanic action.[2]

At places in the Valley the fissures along which the fumaroles are situated show gaping surface cracks for some distance, occasionally with bridges of cemented tuff spanning the rent; but in the more usual case there is merely a furrow or small crack, and even this may be absent.

A definite opening such as mentioned seems to imply either that the fissure has remained open since its formation or that surface material has dropped down into voids below; but since these openings are rather exceptional, it is inferred that when the extrusive activity died down the fissures were in most places left with a filling. This was probably of fragmental, porous material near the surface, but at some unknown depth gave place to material of a denser character.

Occurrences of tuff-filled fissures have been described rather frequently in geological literature,[1] and various explanations of their formation have been offered. It is possible that they have originated in several ways. So far as I am aware, such an origin as is implied by events in the Valley has not been suggested, but is one which should be kept in mind.

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[1] Geikie, op. cit., vol. 1, p. 289.

[2] Op. cit., vol. 1, p. 313.

At the same time, it should not be overlooked that processes which are now at work in the Valley, and which are the natural sequel of the eruptive activity that preceded, are tending to effect transformations that may in the course of time obscure or destroy the original character of the filling.

The fact that large quantities of fumarolic gases are being evolved implies that permeable channels exist in communication with magmatic sources below. The gases appear to be actively at work as agents of deposition, removal, and transformation. Pyrite and other compounds of iron of recent formation are visible around the vents, and, as Zies has found, the incrustations carry a large number of other heavy metals in small quantities. The tuff also is undergoing decomposition, and opaline silica is formed.

Presumably, these depositions and reactions near the surface are an indication of similar processes in the depths. It is to be expected that eventually the mineralizing gases will be replaced by hot waters, and rearrangement of mineral combinations will follow to accord with the new environment.

Finally, a deposit may result having the characteristics of a mineral vein to a greater or less degree, depending upon the length of time these processes continue in operation. Thus it seems probable that it is only in such portions of the fissures as, early in their history, became blocked off as channels of ascent for mineralizing gases, that the original characteristics will be preserved.

NOVARUPTA AND ITS EJECTA

Among the vents of extrusion of sandflow material in the upper Valley, Novarupta is believed to have played an important part. Great activity continued at this point after the sandflow occurred, and during this later period large quantities of pumice and other ejecta were thrown out, though not to a great distance. Gradually this explosive phase subsided, though the magma was not exhausted. The waning of activity may have been primarily due to a slowing down in the rate of supply from beneath, but however this may be, it seems to have been attended by less violent though continuous discharge of

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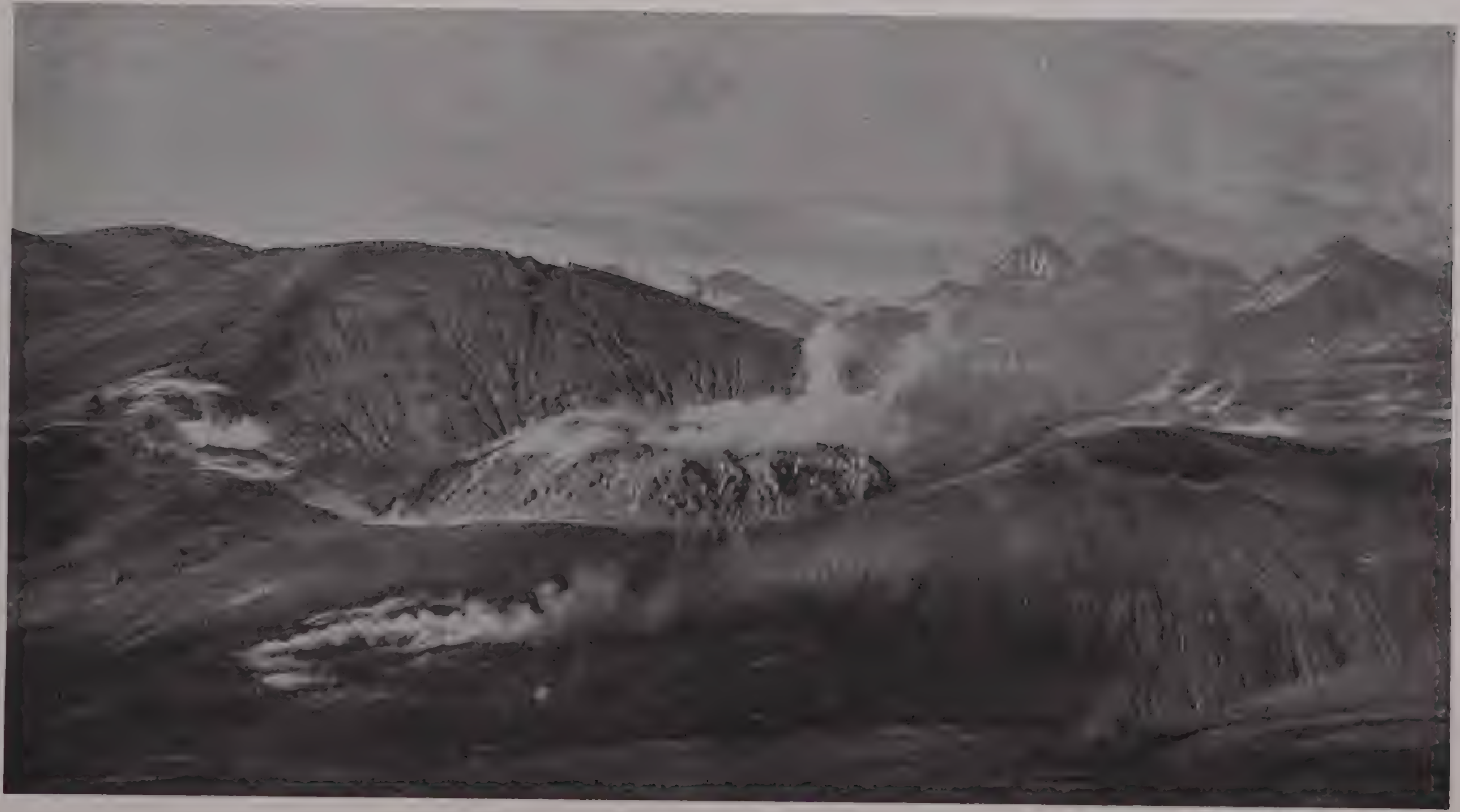
[1] An example of fissure fillings similar to what the Valley might be expected to show is described by J. E. Spurr in Geology of the Tonopah Mining District, Nevada, U. S. Geol. Survey, Prof. Paper No. 42, pp. 47–48, 1905.



Photograph by E. C. Kolb, 1919

NOVARUPTA FROM THE SOUTHWEST

The surrounding crater wall and a large fissure on Broken Mountain back of Novarupta are well shown. In the right foreground one of the conical mounds of rock on the Valley floor between Falling Mountain and Novarupta is visible.

gases, so that finally a body of not yet solidified magma was left from which most of the gases had escaped.

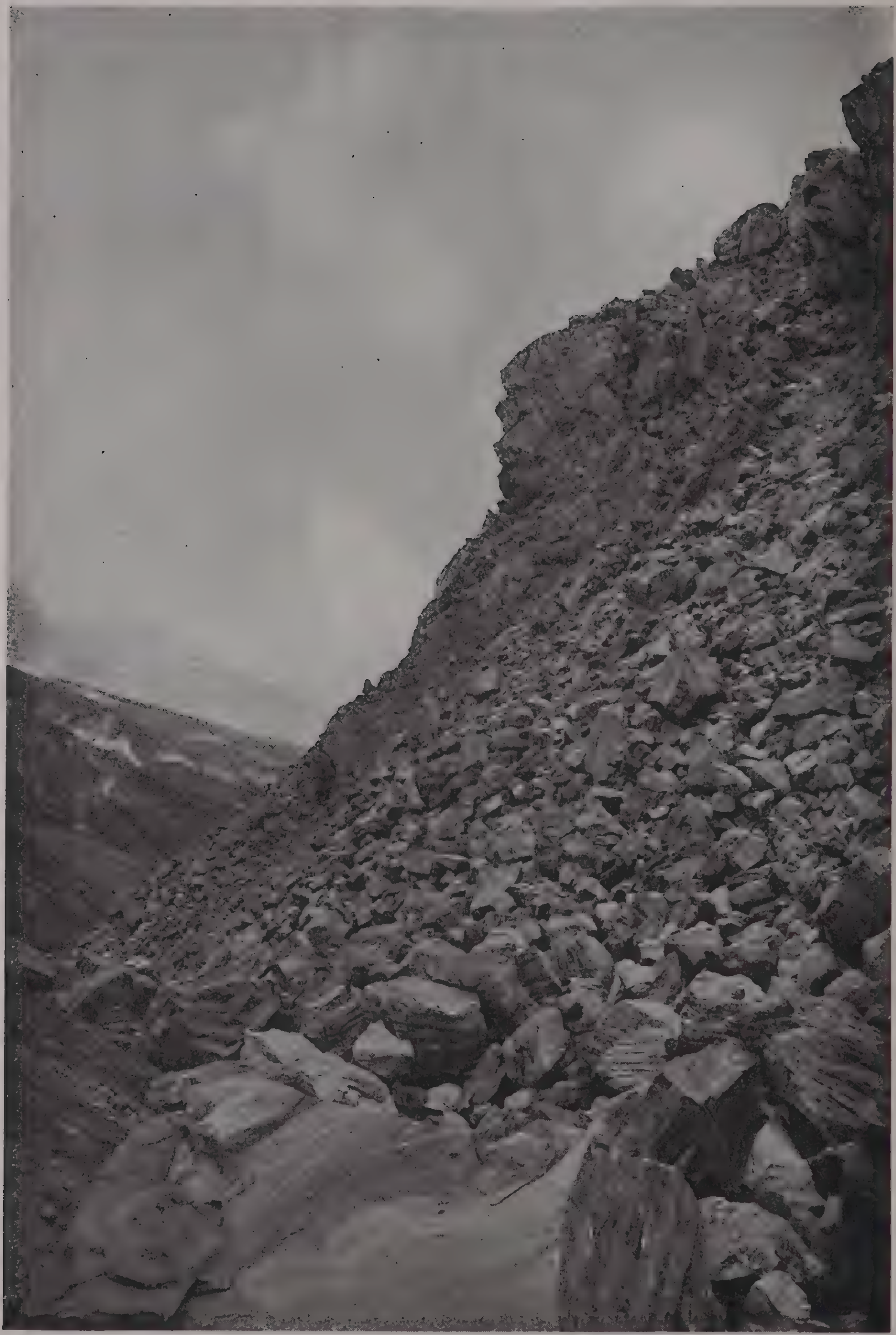
The lessening of the *violence* of discharge seems to have been due largely to the intervention of factors (such as cooling) that affected the *rate* at which gases were evolved. The pressure they were able to exert when they succeeded in escaping from solution was still great, and in even the final stages the small fraction of gas left played an important part. The dome-like mass of viscous magma that finally upheaved itself from the orifice is found, in its consolidated form, to be filled with minute gas pores. From this it is inferred that the enormous opposing pressure at this stage was not sufficient to prevent the gas from coming out of solution, and that this gas pressure itself may well have been the "vis a tergo" that effected the final extrusion.

The present dome is about 800 feet in diameter and 200 feet high. A study of its structure and composition, and of the nature of the material that was previously ejected from the vent, has supplied considerable information in regard to certain features of the tuff deposit. The history of Novarupta appears, in fact, so intimately related to features of the sandflow that it seems well to describe certain of its salient points.

In the description of the make-up of the tuff deposit it was stated that the greater part of the pumice is of a light color and of very siliceous composition, but that part of it is radically different — nearly black in color and carrying basic phenocrysts. These two varieties may occur in the same specimen, giving rise to remarkable banding effects (see page 39), or union may be so complete as to produce a fairly uniform pumice of intermediate composition. To understand how such diverse materials became intimately associated, let us take a look at the make-up of the Novarupta ejecta.

On the lower slopes of Falling Mountain, to easterly of the falling cliff and one-fourth to one-half mile to the south of Novarupta, there are very thick deposits of Novarupta pumice. A great fissure here shows a section 100 feet thick. The pumice is generally very light-colored, though black, gray, and variegated pieces are quite common. There are also black obsidians and blocks of old basic lavas up to two feet in diameter, together with bread-crust bombs.

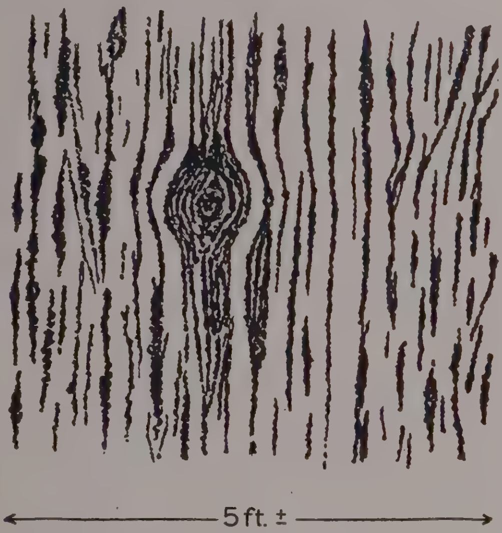
The last consist either of light pumice, variegated pumice or semi-pumiceous glass. One of these having a diameter of 8 feet was found, whose interior consisted of vesicular pumice of the variegated kind. Some of these bombs are made up of a breccia — angular fragments of light pumice and dark glass, together with numerous phe-



Photograph by R. F. Griggs, 1919

PROFILE OF NOVARUPTA, SHOWING BANDED ROCK IN PLACE, AND DISRUPTED BLOCKS, ALSO BANDED nocrysts — in a matrix of dark pumice. A piece of much-blackened shale found here was 6 to 8 inches in diameter.[1]

In the very thick sections of Novarupta ejecta exposed by faults on the top of Broken Mountain similar material is seen — pumice blocks up to a foot in diameter, chiefly white, but also black, brown, variegated, pink, and yellow; Naknek sediments; bread-crust bombs; black obsidian with xenoliths; and blocks of old basic rocks, red, black, purple, and gray, up to two feet in diameter, some in a scoriaceous and apparently partly fused condition. There is quite a definite stratification of these deposits, but no very obvious difference otherwise from top to bottom. A little farther away from Novarupta the proportion of foreign material becomes considerably less.



Diagrammatic sketch of schlieren in Novarupta lava.

Novarupta itself consists of a dome-like mass of generally glassy though slightly porous lava, surrounded by a crater rim of fragmental ejecta (see pages 14, 52, 54, 58). The strata of the rim dip away from the dome at a moderate angle, but on the inward side are cut off sharply and present a steep face to the dome. The intersection of this face with the surface of the dome makes, in general, a V-shaped trough or moat, but locally the moat has a flat bottom.

The height of the crater rim above the floor of the Valley is small on the western side, but in following it around, first southward, then eastward, it rises continually, and on the north it merges with the lower slopes of Broken Mountain. When Novarupta is viewed from a position on Broken Mountain overlooking it, it seems to have broken out not quite on the floor of the Valley, but a little way up the slopes, in the angle between Broken Mountain and the low ridge running across to Trident.

In many places around the rim there are fissures, both radial and approximately circumferential, from which much steam rises. The central pile also gives off clouds of steam, and there are several large patches of sulfur, hundreds of square feet in area, covering the rocks of the pile. In the crater rim the material is the heterogeneous mixture of vesicular pumice, scoria, obsidian, blocks of old lavas and sediments, etc., such as has been described for other deposits near by. There is also material that resembles the gray-colored glass of the dome, and some which shows a transition between that and the vesicular pumice.

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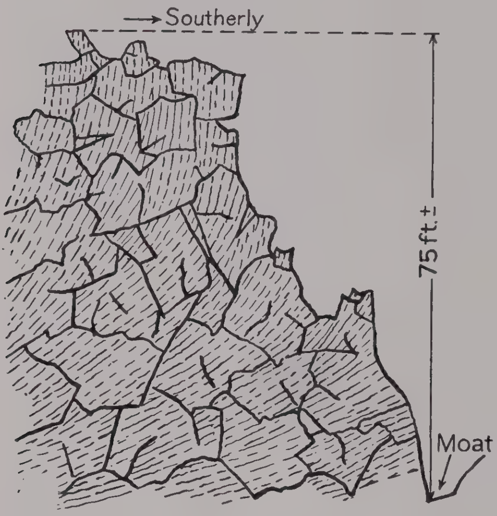
[1] In a previous article on the Katmai region (Jour. Geology, vol. 28, p. 589, 1920) it was stated that the largest pieces of ejected sediments found near Novarupta were about the size of one's fist. In subsequent study of my notes I find occasional mention of the occurrence of rather larger pieces, but the difference is not of material importance.

The outer surface of the dome is pretty well covered with great blocks of broken rock, and many have rolled down into the moat, but nevertheless, much rock in place is seen protruding from the heap (see pages 54 and 60). Here is the only place in the whole region where a mass of non-inflated lava was extruded during the eruptive activities, and here we have the most convincing ocular demonstration of the process by which blocks of basic lava became melted down and incorporated in the new magma.



Diagrammatic sketch of exfoliation structure of Novarupta dome, brought out by banding.

THE COMPOSITE LAVA OF NOVARUPTA

The rock of the dome, both that in place and in the broken-off blocks, is found to have a strikingly banded structure,[1] not here and there but practically everywhere. Part of this is due to alternations of glassy and lithoidal, or glassy and cellular material, such as are often found in rhyolitic flows, but a great part is due to alternations of light-gray [2] glass, almost without phenocrysts, with dark-brown or nearly black scoria often containing great quantities of phenocrysts.

Moreover, distinct inclusions of basic rock, as yet little attacked, may be seen, or scoriaceous-looking masses of partly softened material. One of the latter appears on page 64. On page 55 is reproduced a sketch made on the spot, illustrating in diagrammatic form the relations at one place. It will be noticed that the black bands thin out

[1] This structure might fittingly be described as eutaxitic, were it not that this term has been so intimately associated with the genetic interpretation that has been given to structures of this nature. Loewinson-Lessing, F., Studien über die Eruptivgesteine: Cong. Géol. Int., VII Ses., p. 421, 1897: Iddings, J. P., Igneous Rocks, vol. 1, p. 331, 1909.

[2] In Ridgway's charts, gull-gray to neutral-gray.

and terminate, while the white portion forms a continuous matrix. Page 63 shows the banding very well, and also extraneous phenomena: namely, fracture of the glass while hot, displacement of the parts, and healing of the fracture.

The direction of the banding seems everywhere circumferential to the dome. This was observed to be true for 270° of the circle; the remaining quadrant was obscured by steam. Moreover, near the base the dip is inward at a low angle; near the top it is steep — almost vertical. A sketch of this relation is shown on page 56, made at a place where a cliff-like mass of rock gave a good exposure.

In order to show that the apparent differences of composition are real, chemical analyses of material from light and dark bands in the same hand specimen have been made. The results are as follows:

ANALYSES OF NOVARUPTA LAVA

	153 c (light band)	153 b (dark band)
SiO_2	74.75	62.13
Al_2O_3	13.01	15.29
P_2O_5	.09	
Fe_2O_3	.82	3.43
FeO	1.43	4.53
MgO	.70	2.10
CaO	2.12	5.62
Na_2O	4.32	3.96
K_2O	2.62	1.94
H_2O+	.20	.22
H_2O-	.05	
TiO_2	.28	.70
MnO	.05	n.d.
BaO	.08	n.d.
S	.01	n.d.
Cl	.11	n.d.
Total	100.64	99.92

Fenner, analyst.

There would seem to be little room for doubt about the meaning of such differences. The compositions are those of two greatly contrasted types of rock. The first is a very siliceous soda rhyolite, having almost exactly the composition of the earlier ejecta from Katmai Crater; the second is a medium andesite, which would have appeared still more basic if it were not mingled with a certain amount of the acid material.

It might be contended that the inclusions that have been designated basic lavas are really cognate xenoliths — masses of crystals that have separated from an original magma of intermediate compo-

Photograph by P. R. Hagelbarger, 1918

PROFILE OF NOVARUPTA, WITH FISSURED CRATER WALL OF LOOSE EJECTA, AND MOAT

sition during an intratelluric stage — and that in the process of extrusion these floating masses have become drawn out into the schlieren that we see. This idea is rendered very improbable because of their close resemblance to ordinary porphyritic or aphanitic surface-lavas; also because of their variety, and the evidences of melting-down that they exhibit.

A further objection is that when they are studied in thin sections they are found to be accompanied by much brown glass, for the presence of which the idea of cognate xenoliths does not provide, unless it be contended that the separation of crystals was attended by a splitting of the melt into two immiscible liquid portions. Even for this we find opposing evidence, for the brown glass is seen to mingle freely with the colorless glass of the surrounding magma.

Indeed, we have in this last circumstance evidence against the whole doctrine of liquid immiscibility as generally conceived, for the two liquids that are found to mingle so freely are those for whose separation the hypothesis is supposed to provide: namely, a relatively gas-free basic liquid and a highly gas-charged siliceous liquid.

Besides the blocks of old lavas and the schlieren resulting from their partial fusion, there are inclusions of Naknek sediments. These also give evidences of attack by the magma surrounding them, but hardly to the degree shown by the igneous material.

Novarupta broke through the floor of the Valley at a point where the underlying rock probably consists of sedimentary strata, and the presence of so much old lava in its ejecta and in the rock of the dome offers, at first sight, something of a problem.

Baked Mountain and Broken Mountain are made up entirely of sedimentary strata, and the same is probably true of this area as a whole. Mount Cerberus, Falling Mountain and Mount Trident are igneous, but they seem to mark the limit of igneous rock in this direction.

If, however, we recall Spurr's description of the upper Valley we realize that this locality was the dumping ground for glaciers from the volcanic range, and a great thickness of morainal material was deposited here. This is confirmed by the fact that even Ukak Valley, several miles from the collecting ground of the glaciers, is underlain by a great deposit of boulder till, probably 150 feet thick in places.

Therefore, the blocks of old lava of various sorts found in the ejecta of Novarupta and in the lava of the dome are attributed to morainal deposits derived originally from the mountains to the southeast. A similar explanation would appear probable for the dark-colored and banded pumices occurring in the tuff of the Valley.[1]

INFLATION OF MAGMA DELAYED

The formation of the banded rock by the melting down of old lavas in the new magma seems to be the logical conclusion to which the evidence leads. If we accept it, then we must draw another inference of some importance: When the fissures shattered the floor of the Valley the magma rose in them toward the surface but did not immediately gush out as a great flow, or swell into a pumice from the expansion of its dissolved gases; on the contrary sufficient time elapsed for the unconsolidated deposits at the surface to crumble down into the openings and be partly dissolved before the expansion into pumice and the resulting sandflow occurred.

It seems, therefore, that although the new magma contained

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[1] The total quantity of material of this sort in the Valley deposit is so great, however (see description of sifting test), that it can hardly be supposed that the morainal material over one or a few vents supplied it all, and this gives additional evidence that in the extrusion a considerable number of vents participated. Novarupta had a large vent and was probably a principal contributor, but any reasonable assumption regarding thickness of morainal material here is quite insufficient for the requirements of the whole mass of tuff in the Valley.

Photograph by R. F. Griggs, 1919

SUMMIT OF THE DOME OF NOVARUPTA, SHOWING VERTICALLY BANDED ROCK IN PLACE

great possibilities of explosive action, it was not able to take advantage at once of the removal of physical constraint when the fissures were opened, but required a certain interval, presumably occupied in the rearrangement of internal equilibrium, before the violent intumescence occurred that led to the sandflow.

Probably the liberation of gases, even when set in full operation, required an appreciable period of time, so that there was continuous evolution during the progress of the sandflow. Thus the solid material was partly suspended in and buoyed up by the gas that it was itself evolving. This is inferred both from the remarkable degree of quasi-liquidity displayed by the sandflow and from the fact that in Novarupta, during its last stages, the disengagement of the gas proceeded very slowly indeed, as is shown by the condition of the lava of the dome, which, though now almost free of gas, was not violently ejected by its liberation.

In the Valley of Ten Thousand Smokes the circumstances were probably exceptionally favorable for preserving a record of the magma's history during the short but extremely important period just prior to its sudden expansion. This is because of the fact that basic rocks, very different from the new magma in color and composition, seem to have been accessible to it only when the fissures along which it rose broke through to the surface; also that after more or less complete melting down and mixture had occurred, the whole syntectic suddenly became inflated into a pumice that preserved the stage of incorporation reached.

We are able to see that not only had the deeper-lying portions of the magma held their gases (or a good portion of them) in solution up to a certain critical point, but that the upper portions also, which were under practically no restraining load at this time, and which had been actively engaged in dissolving the surface rocks, had likewise held their gases up to this point of sudden evolution, for they likewise formed pumices. The conclusion drawn is not that unloading was not an essential factor in this explosive development of gas, but that the shift of equilibrium accompanying unloading was of such fundamental character that some time was required for its development after conditions became favorable.

In presenting the evidence up to this point and drawing deductions from it I have endeavored to restrict the field of description and discussion to matters directly related to the tuff deposit and closely associated phenomena. A point has been reached, however, where matters of a fundamental nature, involving volcanism in general, are concerned, such as the state of internal equilibrium in a magma before eruption and the source of the heat required to melt down and incorporate quantities of solid material. Before these matters are discussed in detail, a large amount of evidence that is on hand regarding assimilation during the Katmai eruptions as a whole should be presented, and a separate article will be devoted to these subjects.

COMPARISON OF THE SANDFLOW WITH SIMILAR PHENOMENA ELSEWHERE

It will have been recognized from the foregoing description that the sandflow in the Valley of Ten Thousand Smokes presents many points of similarity to that form of volcanic eruption first carefully observed in the outbreaks of Pelée and La Soufrière in the West Indies in 1902, to which the name *nuée ardente* or glowing cloud has been applied. The important monographs of Lacroix and of Anderson and Flett, to which reference has been made, give a mass of valuable information on the characteristics of these hot avalanches. Concerning their mobility Anderson and Flett say:[1]

> In considering this property of perfect fluidity, which the black cloud possesses, we must remember its origin. Within the crater it was a molten magma, in which a considerable number of small crystals floated in a liquid which contained enormous quantities of occluded steam. As it rose in the throat of the volcano the relief of

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[1] Anderson and Flett, Report on the Eruptions of the Soufrière, in St. Vincent, in 1902, p. 507.

> pressure allowed the gases to expand, and to free themselves from the liquid in which they were held. Sooner or later the cohesion of the liquid was overcome, and from a spongy froth the mass changed to a cloud of particles, mostly solid, but, perhaps, in some part liquid, each surrounded on all sides by films of expanding gases, and thus the mixture of the ingredients from the first was perfect. Around each grain of dust there was a film of gases ready to expand enormously when the mass reached the upper air.
>
> The amount of expansion of which these gases are capable is so great as to be almost incredible. The small black ball of cloud, which we saw emerge on July 9th, in a few minutes was a great black mass, which covered more than a square mile. . . . This leads us to wonder whether, when the cloud emerges, it may not be partly at least composed of molten droplets, which, when they cool and pass into the solid condition as the cloud rolls on, give out gases which, till then, had been physically occluded or absorbed in the liquid. The mere pressure within the crater would almost seem insufficient to compress so great a volume of gas into so small a space, especially when we remember the very high temperature of the mass.

The remarkable fluidity shown by the avalanches in the West Indian eruptions was even exceeded by that in the Valley of Ten Thousand Smokes. According to Anderson and Flett [1] the sides of Pelée and the Soufrière have an average inclination of 12 to 15 degrees. It was down such slopes that the avalanches moved, and, I take it, parts of the material came to rest all along the course.[2] In the Valley of Ten Thousand Smokes the angle of repose finally assumed was only 1° 08′, or a slope of 1200 feet in 11½ miles from the head of the southeastern branch of the Valley down to the morainal hills that separate the Valley from that of Ukak River.

This greater mobility can hardly be ascribed to greater fineness of grain, which might be the first thought. It will be recalled that the sifting test of a sample showed that slightly more than 85 per cent would pass a 10-mesh sieve. In St. Vincent "the most striking feature of the Wallibu deposits was the scarcity of coarse material. Certainly over 90 per cent of the whole could only be described as a volcanic sand, and often the fragments above a couple of inches in diameter did not form over 3 per cent of the mass."[3] At St. Pierre "the materials covering the town consist of fine cinders and of small lapilli, rarely measuring more than 2–3 centimeters."[4]

Elsewhere these writers speak of masses of rock carried by the avalanches,[5] but apparently the percentage of these was in general too small to be much of a factor in affecting the mobility. It may be concluded, therefore, that the greater mobility manifested in the Valley was not because of a greater fineness of material.

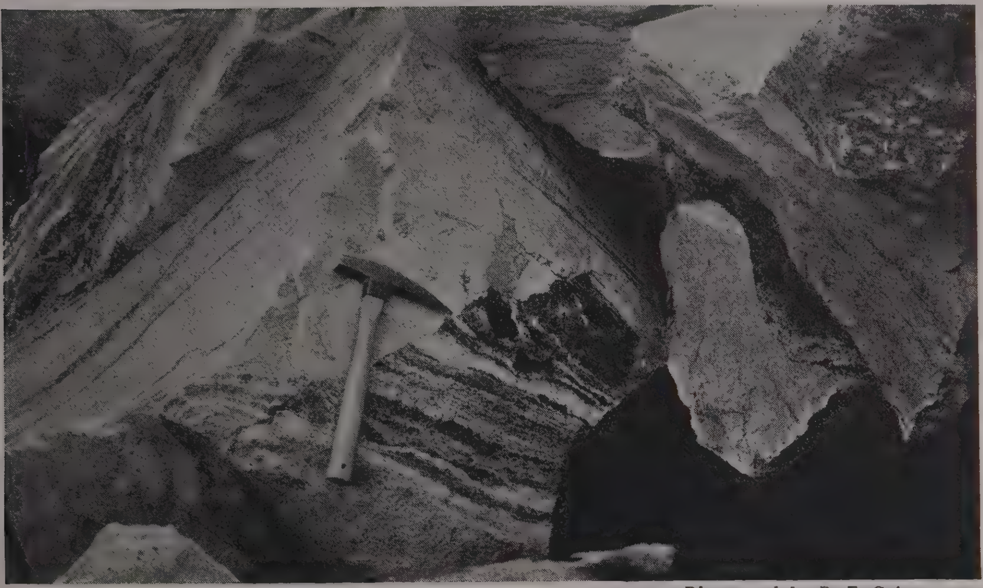
[1] Op. cit., p. 512.

[2] See fig. 70, p. 201, in Lacroix's monograph.

[3] Anderson and Flett, op. cit., p. 432.

[4] Lacroix, op. cit., p. 310.

[5] See, for example, Lacroix, op. cit., p. 212.



Photograph by R. F. Griggs, 1919

BANDED ROCK OF NOVARUPTA

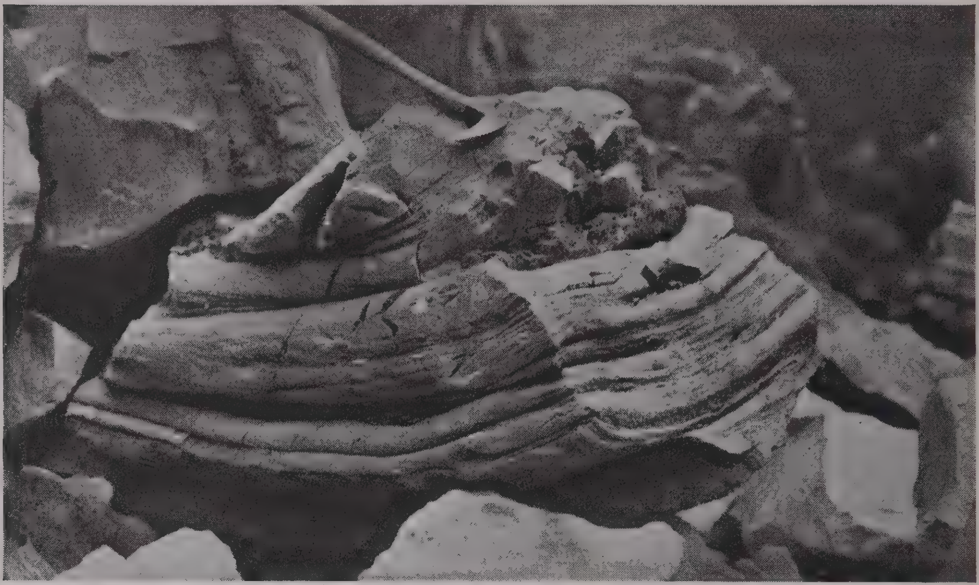
The bands are an alternation of light-colored siliceous glass and dark basic scoria produced by the melting-down of blocks of old lava. The point of the pick rests at a fracture reunited while the material was still plastic.

A matter in which there seems to be a distinct difference, however, is that the proportion of glass to solid crystals was much greater in the Valley than in the West Indian eruptions. Regarding the latter we have the statement:

> All the samples, and notably the Barbados dust, contain a very large proportion of crystalline fragments of volcanic minerals, often broken, but frequently showing perfect crystalline form. Volcanic glass is present also, in fine threads and broken splinters and in thin pellicles, coating the surface of the crystals. . . . From their freshness, their idiomorphism, and other characters, the crystals were formed in a fluid magma, and the glass may be taken to represent the still liquid material at the moment of eruption. If so, it seems clear that such a rock could never have formed a pumice. It is too highly crystalline and contains too little glass.[1]

In the Valley of Ten Thousand Smokes, on the other hand, the material is essentially pumice and fragmental glass. The sifting test showed that in the sample examined (which is believed to be fairly representative) the portion which would pass a 10-mesh sieve (85 per cent of the whole) contained an almost negligible quantity of phenocrysts, and the coarser material was not very different in this respect. It is thought that this much greater amount of glass, which represents the liquid portion of the magma, may have been able to

[1] Anderson and Flett, op. cit., pp. 519–520.



Photograph by R. F. Griggs, 1919

"CORNICE STRUCTURE" IN NOVARUPTA LAVA

A little below the pick a partly melted inclusion of basic lava is visible, and the re-entrant wrinkles mark basic schlieren of partly melted material.

evolve a greater amount of gas, also that this may have prolonged the period of evolution and augmented mobility.

A description given by Frank Perret[1] of the physical characteristics of accumulations of hot dust formed during the eruption of Vesuvius in 1906, which he witnessed at close range, gives interesting information regarding the mobility of such mixtures of dust and gas. In this case, as Perret emphasizes, the dust had been ejected to a height and had fallen and collected upon the slopes, thus having been given opportunity to lose heat and to part with contained gases. Nevertheless it was still very hot and possessed a high degree of mobility, and, at times, masses of it became detached and advanced swiftly down slopes in small avalanches. The transported material filled all hollows with a dry quicksand, in which even small stones sank quickly out of sight. As it cooled, this finely comminuted material became compact, firm enough to support a man.

Lacroix[2] has discussed the relation of the nuées ardentes of Pelée and La Soufrière to certain phenomena attending volcanic eruptions elsewhere, and thinks that a similarity is indicated in a number of cases, among them the eruption of Vesuvius that destroyed Pompeii in 79, and certain eruptions in Japan and Java. The most striking in-

[1] In an unpublished manuscript that I have had the pleasure of reading.

[2] Op. cit., p. 363.

stances of similarity that he found, however, are those of two eruptions of San Jorge in the Azores, in 1580 and 1808.

Regarding these he believes there is no doubt of essential identity, and draws the conclusion that the formation of nuées ardentes is not related to the nature of the magma, since the lava of San Jorge was a very fusible basalt, while at St. Vincent it was a labradorite andesite, and at Mount Pelée a relatively acid andesite. As supporting this inference, we may now add the fact that in the Valley of Ten Thousand Smokes the magma was a very siliceous rhyolite.

From an account given by Omori,[1] it appears that during an eruption of the Asama-Yama in Japan a similar discharge occurred. Omori says:

> Thus the special features of the Temmei eruption (1783) consisted, beside the projection of a great amount of ashes, sands, and red-hot stones, in the outflow of a large quantity of lava, the "Oni-oshidashi," and in the descent of a huge volcanic avalanche. The "Oni-oshidashi," although a highly remarkable and extraordinary object, stopped at the mountain base and did not prove disastrous to the neighboring villages, while the volcanic avalanche produced an enormous amount of damage not only at the mountain base, but for a considerable distance along the courses of the Azuma-gawa and the Tone-gawa.

The initial velocity of this avalanche is believed to have been not under 50 miles per hour.[2]

In the early part of this article I made reference to a description given by Wolf of an outbreak of Cotopaxi in Ecuador on June 26, 1877, and remarked that although Wolf assumed that the extrusion was of liquid lava, the account given by him, based on the testimony of witnesses and on his own observations as to effects, made during a visit in the following September, point strongly to the nuée ardente form of eruption.

After noting an increase of activity of the volcano, beginning about the first of the year and attended by subterranean noises and ejection of ash-clouds into the atmosphere, he proceeds:

> Lava eruption. About 10 o'clock in the morning, therefore, while strong subterranean detonations were heard in different and far-separated parts of the republic, the crater of Cotopaxi boiled over [übersprudelte] with fluid, glowing lava, and this precipitated itself with furious velocity down the declivities of the cone. I chose the words "boiled over" intentionally, because they indicated best the manner and form in which the effusion of lava occurred in this extraordinary outbreak. It happened that at 10 o'clock the southwest side of the mountain and its top were quite clear and free of clouds, so that in Mulaló and Cusiguango, where the rain of ashes had not yet begun, many persons were eyewitnesses of the lava eruption. They de-

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[1] Omori, F., The Eruptions and Earthquakes of the Asama-Yama: Bulletin of the Imperial Earthquake Investigation Committee, vol. 6, no. 1, p. 144, 1912.

[2] Op. cit., p. 112.

> scribed to me vividly the fearful aspect of the mountain as it suddenly came to effervescence (ebullicion) and threw out a "black mass," smoking and steaming, over all parts of the crater edge simultaneously. Naturally they were not united on the nature of the "black mass" (at night it would indeed have appeared fiery); most of them, substituting cause for effect, considered it the water and mud masses themselves. Several used for their description the intuitive picture of a rice pot on the fire suddenly boiling over. For only a few minutes could one observe the mountain in this manner from the southwest side (from the north it had been invisible since 7 o'clock); for it immediately became hidden in the steam generated from the lava, and besides the rain of sand and ashes began immediately to fall in Mulaló. One now heard the awful noise, gradually increasing and approaching, which the rising masses of water and mud caused. . . .
>
> It is indeed one of the singular features of this eruption that the lava poured out of the crater not in one or several streams, but symmetrically in all directions, over its lowest edge as over its highest points. On that account the floods were so general around the mountain. . . .
>
> According to the previous form of the crater the lava in a quiet outflow must pour out preferably toward the east and west, as it did in the last historic eruptions; but this time it held to no rule, it apparently recognized no difficulties of terrain, but precipitated itself, as related, over the highest crater edges as over the lowest, although over the latter apparently in greater quantity. Very many phenomena indicate that the new lava must have possessed a very high temperature at its exit from the crater and must have been almost as fluid as water. Its expulsion occurred suddenly, with a fearful welling-up of the fluid, glowing masses; for only thus is it explicable that in a quarter, or at most, a half hour such a fabulous amount of lava was delivered as the subsequent exact observations on all parts of the mountain showed, and that it flowed out over the highest crater edges like the foam from a "boiling-over rice pot. . . ."
>
> The immediate effects — the great floods of water arising from the melting of the snow — themselves lasted in the valleys hardly an hour.[1]

Wolf then gives an account of the manner in which the mudflows were generated, as I have quoted on an earlier page, and later speaks of the contradictory evidence regarding temperature furnished by great blocks of ice, carried ten miles away, and carbonized tree trunks present in the floods. Regarding the latter he says that those which he saw were in a condition resembling peat or lignite and quite surely were excavated from a bog or moor, but we may suspect that this explanation was devised to account for facts that he could not satisfactorily explain otherwise, and that there had actually been partial carbonization of trees, as has been observed in subsequent hot sandflows with which we are now more familiar.

Wolf made an ascent of the mountain, and during this he saw, in the melted-out channels in the ice, great deposits of lava blocks, sand, ashes, and pieces of old rocks, but there were "no coherent lava streams remaining on the slope of the cone."[2] He does not describe in detail the nature of the new lava, but speaks of its being heaped up, "because of its porous character," at the edge of the mudflow; elsewhere he speaks of pumice. In composition it appears to have been a dacite with numerous quartz phenocrysts.[1]

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[1] Op. cit., pp. 131 et seq.

[2] Op. cit., p. 147.

Wolf's description of the eruption reminds one of the characteristics of nuées ardentes much more than of ordinary flows of liquid lava — the black mass suddenly boiling up and overflowing the rim of the crater on all sides, the prodigious speed with which it precipitated itself down the slopes, the great mass and short duration of the flow, the heavy clouds concealing the mountain within a few minutes, the rain of ashes immediately afterward, the carbonization of tree trunks, the lack of coherent lava flows, the forcible manner in which the outburst spread over valleys and ridges on the upper part of the cone and later flowed down gulches in a more collected form — these point almost irresistibly to this form of eruption.

ESTIMATED VOLUME OF VALLEY TUFF

It is uncertain how many flows the Valley deposit represents, though there are indications that locally there were at least two. On the other hand, its generally massive and unstratified appearance in thick exposures gives an impression that there were not many — perhaps a single principal one.

At any rate, the volume of material is enormous. I have made an attempt to arrive at an approximate figure, but it must be understood that the result represents only a rough approximation at best, because of the uncertainty regarding thicknesses. Those assumed are believed not to be excessive. Figures are as follows:

In Ukak Valley 3 mi.×¾ mi.×10 ft.=627,264,000 cu. ft.
In main Valley 7½ mi.×2½ mi.×100 ft.=52,272,000,000 cu. ft.
In southeast branch 5 mi.×1½ mi.×200 ft.=41,817,600,000 cu. ft.
In south branch 5 mi.×2 mi.×200 ft.=55,756,800,000 cu. ft.

Total=150,473,664,000 cu. ft., or a little more than one cubic mile. Assuming a weight of 90 lb. per cu. ft. for the material in place, we arrive at a weight of about 6,750,000,000 tons. This calculation takes no account of the deposit in Katmai Pass or in the valley of Mageik Creek, which would considerably increase the total, nor of the large amount that must have floated off in the atmosphere.

Even if the thicknesses in the main deposit in the Valley be taken as only one-half of those assumed, the result is still a quantity too large to be easily conceived. The greatness of this mass of material

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[1] Op. cit., p. 125.

CLOSER VIEW OF CANYON SHOWN BELOW

Photographs by E. G. Zies, 1919

MOUND ON WHICH FUMAROLE NO. 33 IS SITUATED in motion may have increased considerably the quasi-liquidity, as the temperature would drop less rapidly than in a smaller mass.

MASS MUCH GREATER THAN WEST INDIAN DEPOSITS

At Martinique and at St. Vincent no such accumulations appear to have resulted from the avalanches. There was a succession of flows, but the thickness of material deposited by each seems to have been small. In reading the accounts of Lacroix and of Anderson and Flett I find some difficulty in obtaining data on depths and areas of distribution that would serve for direct comparison with the deposit in the Valley. This is evidently due to the fact that irregularities of topography caused such irregularities of deposition that precise statements cannot be made. From figures given, however, I get the impression that the magnitude was wholly different.

Lacroix estimates the greatest depth at St. Pierre, after the avalanches of the 8th and the 20th of May, as less than one meter;[1] after the passage of the clouds of the 16th of December and of the 25th of January, the thickness at the seacoast, near the mouth of the River Blanche, 6 kilometers from the crater, is supposed to have been "at least 50 centimeters."[2]

It was apparently only very close to the crater that the deposits were heavy. The cliff-bordered ravine of the River Blanche, situated just under the V-shaped notch of the crater, where it would receive the first overflow, was more than 100 meters deep and had become almost completely filled between October, 1902, and March, 1903.[3]

In St. Vincent the quantity of material erupted seems to have been considerably greater than in Martinique. Anderson and Flett say that "the total mass of material ejected by Pelée may be, perhaps, one-tenth of that which the Soufrière has furnished. The great avalanches of dust which fill the Rabaka and Wallibu valleys enormously surpass in magnitude any deposits of the same kind in Martinique, and the general sheet of deposit over the Soufrière is not only larger, but also probably five times as deep as that which can be found on Pelée."[4]

In the upper part of the valley of the Wallibu Dry River "it was only in the main stream channels that . . . the thickness of the recent accumulation could be ascertained. It was mostly 5 to 12 feet deep."[5] In the narrow valley of the Wallibu River, where it was 400–600 yards wide, the deposit was 60–80 feet thick in places, but this seems to have been local. The illustrations accompanying Anderson

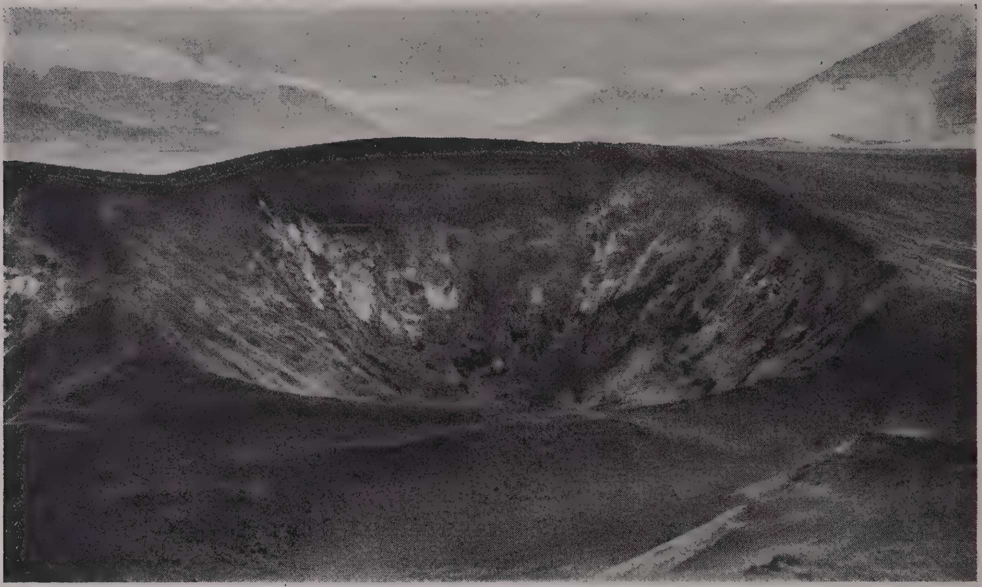
[1] Op. cit., p. 310.

[2] Op. cit., p. 210.

[3] Op. cit., p. 211.

[4] Op. cit., p. 488.

[5] Anderson and Flett, op. cit., p. 429.



Photograph by R. E. Helt, 1919

ONE OF THE MANY CRATERS IN THE SANDFLOW IN THE SOUTHEAST BRANCH OF THE VALLEY

Such craters are found frequently at the summits of mounds.

and Flett's treatise convey an impression of only moderate quantities as compared with the Katmai occurrence.[1]

In discussing the probable mechanism of the formation of a dust cloud, Anderson and Flett express the opinion that the large proportion of nonextensible crystals present in the eruptions studied by them was an important factor in effecting rupture to a fine dust.[2] In the Katmai example, however, this factor cannot be invoked for though crystals were rare, a similar degree of rupture resulted.

THE MECHANISM OF THE EXTRUSION AND DISPERSAL OF THE TUFF

As to what determines whether a gas-charged magma shall explode in an extremely violent manner or in the more quiet form that produces a sandflow, our information seems hardly sufficient for an answer. It is important to observe, however, that the portion of the magma that rose by a presumably direct route into Katmai Crater exploded in a violent manner, while that portion, of apparently identical composition, that found its way by somewhat devious channels into the fissures of the Valley and probably was cooled during this process, erupted in the hot avalanche form.

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[1] In this comparison the amount of material thrown into the atmosphere and carried off as dust is not taken into consideration. Anderson and Flett, from a calculation of the amount that fell on Barbados, believe it not impossible that in the eruption of La Soufrière on May 7th several billion tons of solid matter were projected into the air (p. 418). In the Katmai region the floating dust from Valley vents cannot be distinguished from similar material from Katmai Crater.

[2] Op. cit., p. 520.

The exception to this presented by Novarupta, which manifested explosive activity succeeding the avalanche, is interesting from the fact that this vent is one of the nearest of those in the Valley to the volcanic range, under which is thought to have been the source of supply, and that its large size would render the cooling effect of the walls less pronounced.

So far as this evidence goes, it seems to indicate that with a given magma a portion whose original heat supply has been considerably diminished during its ascent to the surface is less likely to explode with extreme violence than one which has retained more of its heat.

Anderson and Flett [1] have expressed the view that in the avalanches from Pelée and La Soufrière "gravity did the work and supplied the energy. There was no explosion." This is not incompatible, of course, with their further statements:

> But these discharges are not mere avalanches; they are more, for they have properties unlike those of avalanches, and by means of which they approach more closely to blasts. . . . In an ordinary avalanche the gases are more or less accidentally involved, and form only a small part of the whole mass. . . . But here their presence is essential; they are an original part of the mass, and without them there would be no flow.

Lacroix,[2] on the other hand, while admitting the importance of gravity as a factor and citing proofs of its influence, believed that at Pelée an initial explosion was essential. According to his view, the outburst of the clouds was immediately preceded by an explosive rupture of the shell of the dome, and this governed the direction taken.

> I have shown above that at least for the clouds that I have studied, the lavas must have left the dome almost wholly in the solid state; it is then not possible to make their consolidation during the progress of the clouds intervene as a source of vapor. . . . An initial explosion appears to me necessary to explain not only their outbreak, but even, in certain cases, the direction followed by them.

It is not pertinent to our purpose to attempt to decide between these observers as regards the regions they have discussed, but it is desirable to determine, if possible, what occurred in the Valley of Ten Thousand Smokes. Here, however, a conservative attitude must be taken, as only inferences can be drawn regarding unobserved phenomena. However, the degree of importance that I would attach to the various factors here would be somewhat different from that of either

[1] Op. cit., p. 510.

[2] Op. cit., p. 352.

of the other observers, although the conception closely resembles that of Anderson and Flett.

I think that initial explosions from vents situated on the floor of the Valley could hardly have had much effect as directive agents in the movement, nor would gravity produce the observed results unless the material itself possessed most unusual properties.

I would, therefore, stress the remarkable character imparted to the dust-and-gas mixture by a continuous evolution of gas, which must not only have eliminated almost completely the contact friction of the particles, but also have tended to drive them apart somewhat forcibly and caused the mass to spread almost as freely as a true liquid.

Naturally, gravity would act upon a mixture that was undergoing the assumed reactions just as it would act upon a liquid, and would direct its course down the slope of the Valley, but the important fact to be emphasized is the manner in which internal friction of the mass was eliminated, and it seems to me that only in some such way as that suggested would it be possible for this to be accomplished.

As to the nature of the gases given off by the magma in the Valley, there is no evidence except that derived from the study of the gases now evolved from the fumaroles, and this, while pertinent, is not direct. There is likelihood that the products of the first great outburst of gases from a liquid magma brought suddenly into an entirely new environment would be somewhat different in the proportions of constituents from those evolved during the slow cooling of a body of magma at depth. In the Antillean eruptions there is good evidence that the chief gaseous constituent was water, with sulfur compounds present in noticeable amount. From general considerations, these same substances may reasonably be inferred to have played the chief part as explosive agents at Katmai, together with a considerable number of other substances in minor amounts.

In this article the view has been taken that the magma that rose in the fissures in the Valley, though potentially explosive, did not explode at once when it rose to the surface, but that a considerable time elapsed before the shift of internal chemical equilibrium had progressed so far as to lead to the climax. It is not thought that this magma was exceptional in this respect, but that a similar course is often followed in explosive eruptions.

It is interesting to read the accounts of the phenomena at Pelée and La Soufrière with this conception in mind. Although the conditions that favored a preservation of the record of events in the Katmai eruptions were not present in the others, we know at least that after the magma had risen into the craters at Pelée and La Soufrière, and when there seemed to be no physical obstacle to immediate explosion, a period of gradually increasing violence intervened before the climax came. Moreover, the explosive discharge, once started, did not continue until the magma was exhausted, but successively lower layers, when relieved of their superincumbent load by the ejection of material higher in the conduit, experienced in turn a period of relative quietude, followed by increasing activity, and finally by explosive ejection.[1]

At Pelée the presence of the "spine" complicated matters somewhat, but for La Soufrière it seems a reasonable hypothesis that pauses in activity were required for the development of a new chemical equilibrium, as has been suggested for the vents in the Valley of Ten Thousand Smokes.

A remarkable feature of the Valley deposit, and one that has not yet been discussed, is that, although there is good reason to suppose that extrusions took place from a number of vents, it appears as if all the extrusions were nearly simultaneous. This is inferred from the concordance of slope of the surface over the whole deposit; there is nothing to suggest a division into areas occupied by materials from separate vents. However, with material of such mobility, the same result might perhaps be attained if ejections occurred over an interval of time, and we may not be compelled to assume contemporaneity. This is a matter upon which more evidence would be desirable from a careful study of the deposit in many places with this point in mind.

The contemporaneity of action that is suggested would be quite remarkable, but probably not more so than the fact that Pelée and La Soufrière, 63 miles apart, broke out at almost the same time, the first nuée ardente at La Soufrière having occurred at 1.55 p.m. on May 7th and the first at Pelée at 8.02 a.m. on May 8th.

Undoubtedly, the eruptive phenomena known as nuées ardentes are not as rare as was supposed when the Antillean eruptions of 1902 were first made known. It should be remembered, however, that not all volcanic avalanches possess the essential features of the nuées ardentes. At times the simple effect of gravity upon an accumulated mass of hot ejecta may start movements, as was the case in the ash slides on Vesuvius witnessed by Perret, referred to on a previous page; again a violent initial explosion may be the chief factor, with which gravity coöperates, to set an inert mass in motion, an example of which was furnished by Bandai San in Japan in 1888; but although both of these may play a part in the development of the typical nuée ardente, I believe that they alone are not sufficient and that a third factor is essential.

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[1] See "The Stages of the Eruptions" as given by Anderson and Flett, op. cit., p. 500.

This, as I conceive it, is the self-explosive property inherent in the magma itself, due to the presence and evolution of dissolved gases; and this explosive evolution is not manifested immediately, but is prolonged over a considerable portion of the time during which the spreading movement continues, and gives to the material its fundamental characteristics of quasi-liquidity. Gravity plays an important part in directing the flow down mountain slopes or along topographic depressions, but it is believed that its effectiveness would be rather insignificant were it not for the peculiar properties imparted by the form of disintegration described.

In conclusion, I wish to express my indebtedness in relation to this article as a whole to my colleagues of the Katmai Expedition of 1919 and of the Geophysical Laboratory. The description of facts and the formulation of views expressed here are both due in large measure to the free interchange of information and the discussion of opinions among us. My thanks are due especially to Professor R. F. Griggs, Dr. E. T. Allen, and Dr. E. G. Zies.

Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D. C., July, 1922.

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